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AN ANALYSIS OF FURNITURE HEAT RELEASE RATES BY THE NORDTEST

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ABSTRACT

This report analyses the small to full-scale prediction of the combustion behaviour of a series of Nordtest furniture specimens. This prediction analysis is based on *Model I* from the Combustion Behaviour of Upholstered Furniture (CBUF) study. The Nordtest furniture specimens ranged from 1 to 3 seaters and used two different types of foam and fabrics. Both types of foam and fabric were representative of the two extremes typically found on the market.

The foams used were *High Resilience Polyurethane* and *Standard Polyurethane.* The fabrics used were 100% polypropylene and 100% cotton/linen blend.

A total of 141 full-scale furniture tests in the Furniture Calorimeter and 33 small-scale tests in the Cone Calorimeter were conducted at the fire-testing laboratory at CSIRO in Melbourne. In addition to this a further 22 small-scale tests in the Cone Calorimeter were conducted in the fire-testing laboratory in Christchurch at the University of Canterbury.

The outcomes from this study showed that *Model I* is a good predictor of the full-scale results for the *Standard Polyurethane* foam with both fabric combinations. The *High Resilience Polyurethane* foam burnt more readily with its cotton/linen fabric cover than with the polypropylene fabric, demonstrating that fabric effects can be quite pronounced in determining the burning behaviour of upholstered furniture.

The *High Resilience Polyurethane* was a better performer than the *Standard Polyurethane* foam, in terms of producing a lower heat release rate, and was generally over predicted, confirming that for these particular furniture specimens, *Model I*'s results range from good to conservative.

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NOTE **Bold entries** are figures reproduced from the CBUF Report (Sundstrom 1994)

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1 INTRODUCTION

For a long time concern has been expressed about the fire properties of furniture, this concern has increased especially as it becomes more and more common to construct furniture from synthetic based materials. Most furniture today is constructed from a combination of plastics and polyurethane foam, which from experimental studies has demonstrated significantly faster heat release rates and higher heat release peaks than the traditional cellulosic-based furniture. This is doubly serious when coupled with the fact that in most residential premises, furniture is the dominant fuel load. Cropp (1991) found that in New Zealand 90.7% of all fire related deaths occurred in residential premises (residential is defined in the study as any building where people sleep). These statistics are of similar proportions in other Western countries.

It is the purpose of this research project to predict the free burning heat release rates for furniture items so that further predictions can be made about their relative hazards, when placed in compartments. Once the general heat release rate for a particular furniture item is known, its' burning characteristics in a compartment can be determined. Depending on the size, ceiling height and lining materials of compartment, the proximity and flammability of other items near to the burning item accurate predictions can be made as to whether and when flashover of the compartment will result. The basis for these predictions are based primarily on experimental correlations, which are derived by statistical analysis from the results obtained via the Cone Calorimeter tests. It is thus vital that the cone samples are constructed from the representative materials and in the same appropriate style that the full-scale furniture item is. From the results of these tests the distinguishing fire parameters, (peak HRR, total heat release, time to peak heat release, etc) are scaled into a series of correlations from which predictions on the full-scale burning behaviour are derived.

These correlations are statistically based and have been formulated from the comparison of many hundreds of small-scale tests (Cone Calorimeter) and free-burning full-scale tests (Furniture Calorimeter). This research was conducted in fire testing laboratories throughout Europe in a joint research effort called CBUF, (Sundstrom 1995). From these results further comparisons were made with room burns (Room Calorimeter), when the furniture specimen was burnt in a standard compartment. The time to untenability and room flashover have also been correlated. These tests have now all been compiled in a database which practitioners can use in the future prediction of furniture hazard.

1.1 Hazard Assessment

As part of a fire hazard analysis, it is necessary to estimate the burning characteristics of selected fuels (in this case a furniture item) and their effects in compartments. Of secondary importance is a reliable prediction of when fire protection devices such as heat and smoke detectors or automatic water sprinklers will activate. The predictors of a fire hazard are usually based on the combination of three things. The first and most important is a knowledge of how fast the fire grows (a heat release rate and flame spread problem). The second is knowing how severe is it (what is the duration and height of its' peak heat release rate?). The third is to be able to reliably predict the time to the onset of life-threatening (untenable) conditions (dependent on nature of combustibles, fire size and compartment of fire origin). We base the predictors of hazard on these variables, as once the fire is ignited, it is these factors which determine how much time occupants in a building have to safely evacuate. It must be noted that no fire behaves in the same predictable manner even when every attempt is made to keep the variables of an experiment the same. There are literally thousands of different chemical reactions that manifest themselves in a combustion reaction. This complexity inherent in any fire reaction leads us to only be able to describe it in very general terms. The size of a fire which is defined by its' heat release rate, is at present one of the most useful parameters used. The primary equations for calculating this parameter are based on oxygen consumption calorimetry and are described briefly in the next section.

1.2 Heat Release Rate

When an item undergoes a combustion reaction it releases energy. The rate of this energy release is dependent on the nature of the fuel, its' material properties such as heat of combustion (ΔH_c) and the fire environment; the manner in which the fuel is volatilised in conjunction with the efficiency of the vapour combustion. This is at present too hard a problem to solve exactly, so we must tackle it from another direction. The principle of oxygen consumption calorimetry has made the measurement of the rate of heat release a reality. It is still necessary to rely on available experimental test data for the specific or related fuels to maximise accuracy.

1.2.1 Heat Release Rate Equations

The equations, which govern the heat release rate from a burning object, using the principles originated by Thorton, for the Cone and Furniture Calorimeter are summarised below. These equations are derived from the work conducted by Parker and Janssens and can be found described in greater detail in their published article, which is referenced in this report. The prediction of heat release rate increases in accuracy as you increase the number of gaseous by-products measured. Thus to just simply measure the consumption of oxygen provides the least accurate measurement of heat release rate, while to measure the consumption of oxygen, increase in carbon dioxide, carbon monoxide and water vapour yields the highest accuracy, but also presents the most difficulty in measurement complexity.

1.2.1.1 The heat release rate when just O_2 gas is measured

$$\dot{q} = E\phi X_{O_2}^{A^o} \frac{M_{O_2}}{M_a}\left(\frac{\dot{m}_e}{1+\phi(\alpha-1)}\right)\left(1 - X_{CO_2}^{o} - X_{H_2O}^{o}\right)$$

where

$$\phi = \left(\frac{X_{O_2}^{A^o} - X_{O_2}^{A}}{X_{O_2}^{A^o}\left(1 - X_{O_2}^{A}\right)}\right)$$

and

$$\dot{m}_e = \frac{Ak_c}{f(\mathrm{Re})}\sqrt{\left(\frac{2M_{dry}\,\rho\Delta P}{M_e}\right)}$$

1.2.1.2 The heat release rate when just O_2 and CO_2 gas are measured

$$\dot{q} = E\phi X_{O_2}^{A^o} \frac{M_{O_2}}{M_a}\left(\frac{\dot{m}_e}{1+\phi(\alpha-1)}\right)\left(1 - X_{H_2O}^{o}\right)$$

where

$$\phi = \left(\frac{X_{O_2}^{A^o}\left(1 - X_{CO_2}^{A}\right) - X_{O_2}^{A}\left(1 - X_{CO_2}^{A^o}\right)}{X_{O_2}^{A^o}\left(1 - X_{O_2}^{A} - X_{CO_2}^{A}\right)}\right)$$

and

$$\dot{m}_e = \frac{Ak_c}{f(\mathrm{Re})}\sqrt{\left(\frac{2M_{dry}\,\rho\Delta P}{M_e}\right)}$$

1.2.1.3 The heat release rate when just O_2, CO_2 and CO gas are measured

$$\dot{q} = \left(E\phi - \left(E_{CO} - E\right)\right)\left(\frac{(1-\phi)}{2}\frac{X_{CO}^{A}}{X_{O_2}^{A}}\right)X_{O_2}^{A^o}\frac{M_{O_2}}{M_a}\left(\frac{\dot{m}_e}{1+\phi(\alpha-1)}\right)\left(1 - X_{H_2O}^{o}\right)$$

where

$$\phi = \left(\frac{X_{O_2}^{A^o}\left(1 - X_{CO_2}^{A} - X_{CO}^{A}\right) - X_{O_2}^{A}\left(1 - X_{CO_2}^{A^o}\right)}{X_{O_2}^{A^o}\left(1 - X_{O_2}^{A} - X_{CO_2}^{A} - X_{CO}^{A}\right)}\right)$$

and

$$\dot{m}_e = \frac{Ak_c}{f(\mathrm{Re})}\sqrt{\left(\frac{2M_{dry}\rho\Delta P}{M_e}\right)}$$

1.2.1.4 The heat release rate when O_2, CO_2, CO and H_2 gas are measured

$$\dot{q} = \left(E\phi - \left(E_{CO} - E\right)\right)\left(\frac{(1-\phi)}{2}\frac{X_{CO}^{A}}{X_{O_2}^{A}}\right)X_{O_2}^{A^o}\frac{M_{O_2}}{M_a}\dot{m}_a\left(1 - X_{H_2O}^{o}\right)$$

where

$$\phi = \left(\frac{X_{O_2}^{A^o}\left(1 - X_{CO_2}^{A} - X_{CO}^{A}\right) - X_{O_2}^{A}\left(1 - X_{CO_2}^{A^o}\right)}{X_{O_2}^{A^o}\left(1 - X_{O_2}^{A} - X_{CO_2}^{A} - X_{CO}^{A}\right)}\right)$$

and

$$\frac{\dot{m}_a}{M_a} = \frac{\left(1 - X_{H_2O}\right)\left(1 - X_{O_2}^{A} - X_{CO_2}^{A} - X_{CO}^{A}\right)}{\left(1 - X_{H_2O}^{o}\right)\left(1 - X_{O_2}^{A^o} - X_{CO_2}^{A^o}\right)}\frac{\dot{m}_e}{M_e}$$

and

$$\dot{m}_e = \frac{Ak_c}{f(\mathrm{Re})}\sqrt{\left(\frac{2M_{dry}\rho\Delta P}{M_e}\right)}$$

Because different techniques are used to measure the mass flow rate $\boldsymbol{m_e}$, in the Cone (orifice plate) and Furniture Calorimeter (bi-directional probe), it is described specifically for these two situations below.

For the Cone Calorimeter using an orifice plate

$$\dot{m}_e = C\sqrt{\frac{M_{dry}\Delta P}{M_e T_e}}$$

For the Furniture Calorimeter using a bi-directional probe

$$\dot{m}_e = 26.54\frac{Ak_c}{f(\mathrm{Re})}\sqrt{\frac{M_{dry}\Delta P}{M_e T_e}}$$

Where

q	=	Heat Release Rate	(kW)
E	=	Heat released per O_2 consumed (13.1 $MJkg^{-1}$ of O_2)	($MJkg^{-1}$)
E_{CO}	=	Net heat release per unit mass of O_2 consumed for combustion of CO to CO_2 (=17.6$MJkg^{-1}$ of O_2)	($MJkg^{-1}$)
ϕ	=	Oxygen depletion factor	(--)
C	=	Orifice Calibration Constant	(--)
α	=	Expansion factor	(--)
k_c	=	Velocity profile shape factor	(--)
A	=	Cross-sectional area of the duct	(m^2)
ρ	=	Density of the exhaust gases	(kgm^{-3})
f(Re)	=	Reynolds number correction if Re > 3800 then f(Re) = 1.08	(--)
ΔP	=	Orifice or bi-directional probe differential pressure	(Pa)
T_e	=	Exhaust gas Temperature (at orifice)	(K)
M_a	=	Molecular weight of the incoming air	($kgkmol^{-1}$)
M_e	=	Molecular weight of the exhaust gases	($kgkmol^{-1}$)
M_{dry}	=	Molecular weight of dry air (29 $kgkmol^{-1}$)	($kgkmol^{-1}$)
m_e	=	Mass flow rate of the exhaust gases	(kgs^{-1})
m_a	=	Mass flow rate of the incoming make-up air gases	(kgs^{-1})
X_{O_2}	=	Measured mole Fraction of O_2	(--)
X_{CO_2}	=	Measured mole fraction of CO_2	(--)
X_{H_2O}	=	Measured mole fraction of H_2O	(--)

X_{CO} = Measured mole fraction of CO (--)

For the superscripts above the mole fraction symbols above, the definitions are:

A^0 represents the measured gas in the analyser in the incoming make-up air.

A represents the measured gas in the analyser in the exhaust gases.

Although these procedures are relatively straightforward in principle to apply, there is a caveat when doing so for practical applications. The main problem is related to the delay in response of the instrumentation in the exhaust duct. This delay is actually a combination of two factors. The first is the time required for the combustion products to travel from the fire to the measuring point in the duct, which is termed the transport time. The second delay is the response time of the gas analysers, which is called the response time. Although not exact, very accurate answers can be obtained by shifting the measurements over the appropriate transport and response time intervals.
For cases where this delay time is uncertain or quite significant it is possible to run a calibration test with the ignition source. Such a test yields a baseline heat release rate curve against which the subsequent real tests can have subtracted, to achieve the correct result. Further elucidation on the equations and methods used for measuring heat release rates, as presented by Janssens and Parker can be found in Enright 1995, which is listed in the **References**.

2 REVIEW OF PREVIOUS WORK

It has long been known that it is not the building that poses the fire hazard, but what you put in it. With the introduction of many new and innovative building furnishing products – predominantly thermoplastic in nature, the risk has now spread to wall linings and surfaces. It is thus an increasingly important area of Fire Engineering to be able to accurately assess a fire hazard. For this to be possible it is necessary that both qualitative and quantitative measurements can be made on the fire parameters that dominate a fire hazard. These parameters are heat release rate (HRR), flame spread and rate of increase of life threatening toxicity products. Most, however, are governed by the HRR.

2.1 Historical perspective

Heat release has long been recognised as the major fire parameter because it defines fire size. This in turn defines many of the other parameters of fire and it's reactions, namely smoke and toxic gas production. These characteristics are most often wholly dependent on fire size. It is thus viewed as an essential component of fire protection engineering that the ability to accurately predict the heat released from common building furnishings, storage goods and materials is possible. This prediction must be based on precise and accurate measurement of the heat release data for the materials under study. Such essential data did not generally become available until the 1980s when a practical technique for measuring heat release rates was developed.

This technique for measuring heat release rate (HRR) occurred when W. Parker & C. Huggett re-discovered the long obscure principle of oxygen consumption in the late 1970s. Oxygen consumption originated in 1917 when Thornton showed that for a large number of organic liquids and solids, a more or less constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. Huggett (1980) found that this was also true for organic solids and obtained an average value of 13.1 $MJkg^{-1}$ of O_2. This value may be used for practical applications and is accurate with very few exceptions to within 5%. Thornton's rule implies that it is sufficient to only measure the oxygen consumed in a combustion system in order to obtain an accurate determination of the net heat released. Parker (1980) published detailed instructions on how to carry out and obtain the heat release data from combustion experiments. Janssens (1991) revised Parker's equations, putting more emphasis on full-scale fire test applications and removing the necessity for measuring volumetric flow rates. The basic requirement is that all the combustion products are collected and removed through an exhaust duct, where at a distance downstream, sufficient for adequate mixing, both flow rate and the composition of the gases are measured. As well as measuring the oxygen consumption, Janssens & Parker (1992) state that improved accuracy can be obtained if the concentrations of CO_2, CO and H_2O are measured also. They included equations for these situations in their paper. This technique has gained considerable support and there are now more than 25 laboratories working with large-scale oxygen consumption calorimeters. Bench-scale oxygen consumption calorimeters have been designed with a number of different geometries, but the most common is the Cone Calorimeter, which has become the standard test method for heat release measurement.

It is a well-known fact that in most cases it is not the building, which creates the fire hazard, but the furnishings, or materials placed inside it. For a long time concern has been expressed about the fire properties of furniture. This concern has grown, as synthetic based materials become the dominant choice in furniture construction. Most furniture today is constructed from a combination of plastics and polyurethane foams, which from experimental studies has demonstrated achieve significantly higher peak heat release rates, in much shorter times, than the traditional cellulosic based furniture. In addition to this when combined with synthetic fabric covers, ignition success rates increase. This is doubly serious when coupled with the fact that in most residential premises, furniture is the dominant fuel load.

During the late 1960s, furniture flammability started to be re-evaluated in the light of four developments. The first of these was the rapid advances being made in fire protection engineering; both in the understanding and engineering solutions to post-flashover fires, and also to the spreading, pre-flashover fire. Second was the increasing use of plastics and polyurethane foam in the construction of furniture. Third, some spectacular fires occurred, whose rapid spread and fast burning rates being attributed directly to furniture. The most notable of these fires was probably the fire in the BOAC facility at Kennedy International Airport in 1970, (Abbott 1971). Fourth was the high percentage of fire deaths which were a direct result of small pre-flashover furniture fires in the residential sector, usually initiated by cigarette ignition, (Clarke 1976). The National Bureau of Standards (NBS) started a research program in 1972 (Vickers 1972) on furniture cigarette ignition resistance requirements, which culminated in a 1972 recommendation for a test standard (Loftus 1978).

However it is the potential for room flashover that is the most critical condition in the hazard assessment of a fire scenario. (Flashover is defined as a change from localised burning to fully stirred burning in a room. Prior to flashover, temperatures and heat fluxes are generally near ambient, except near localised zones of burning. After flashover the entire combustible contents of the room are burning and the fire is out of occupant control). With flashover the potential for the fire to rapidly spread to other areas of the building increases dramatically. This question of what conditions are necessary for flashover to occur are not easily answered, but several studies made progress in describing prescriptors that led to room flashover. In 1975 Jansson et al. showed that 600^0C was the minimum gas temperature required for room flashover. This was determined through visual observation of flames emerging from the windows of the fire compartment inside which the furniture test items were burning. Prior to 1980 it was known that no one furniture item could in isolation cause a room to flashover. This situation has changed however, with synthetically constructed furniture. From research recently conducted at CSIRO it has been found that several highly padded domestic (lounge) single seat armchairs can reach a peak HRR just under 2MW (Webb et al., 1999), in the ASTM room (total heat release 262 MJ). This produces more than sufficient energy to raise the temperature in the upper layer well above 600^0C, a major criterion for causing room flashover (Thomas 1981). Similar but free-burning Furniture Calorimeter experiments conducted on exemplary New Zealand furniture at the University of Canterbury (Enright 1998) yielded peak heat release rates of between 0.9 to 1.7MW and total heat releases of between 150 to 387MJ. The CBUF study (Sundstrom 1995) also found that highly Polyurethane foam padded chairs had sufficient heat release rates to singly cause a room to flashover. Several studies (Fang 1975) were conducted examining the critical heat fluxes produced and required for piloted ignition by adjacent furniture items to that initially burning.

Beitel et al. 1976 at the Southwest Research Institute conducted a fire study sponsored by the Products Research Committee. Two fully furnished living rooms were tested, one with furniture, including upholstered chairs, characterised as 'traditional," the other as "plastic." The construction of the upholstered chairs was in fact identical, except that the "plastic" furniture utilised polyurethane foam, instead of "traditional" cotton batting cushioning. The furniture was ignited with a gas burner. The plastic-furnished room exhibited a faster developing and more severe fire.

At the British Fire Research Station (FRS) (Palmer & Tayler 1976) and Rubber and Plastics Research Association (RAPRA) a total of 19 fully-furnished living rooms were burned, with the upholstered specimen being ignited first. In these tests, no rooms furnished with traditional (no foam or plastic fabric) furniture reached flashover, but certain of the ones using foam and plastic materials did. Adequate ventilation was also necessary. Some of the foam and plastic padded specimens burned so fast that their wooden frames could not be adequately ignited before the fire burned out. The traditional items by contrast, however burned out slowly and completely. Poly (vinyl chloride) and viscose/wool fabrics were seen to reduce the burning rate, while polypropylene fabrics enhanced it.

Polypropylene and other thermoplastic fabrics were shown to behave poorly when covering foam. This was because, when subjected to heating, these materials rapidly shrank and pulled away, leaving the foam bare. Since the presence of almost any covering over the foam can reduce flame-spread rate several fold, it is evident that this shrinking away behaviour is undesirable. Wool fabrics and natural hide products were the most successful in protecting the underlying foam. Other findings were that fire performance of polyurethane foam/thermoplastic fabric combinations could be improved by providing a cotton fabric interliner, or even better ones treated with ammonium bromide/urea fire retardant. The recommendations from this research study advised furniture manufacturers that upholstery fabrics should not be drawn too tight, to lessen the chance of early splitting. Flaked (foam crumb) foam cushions especially need a good interliner, due to their increased surface area. The avoidance of cigarette traps, and that in view of the fact that vertical surfaces burn approximately three times as fast as horizontal ones, the possibilities of using furrows as fire breaks be considered. The RAPRA study summarised much of all the previous research on foams and fabric effects although it placed most emphasis on materials in common European usage.

Work on interliners and fire retardant materials is a major research initiative and is still continuing.

It is from this point onwards that CBUF (Combustion Behaviour of Upholstered Furniture) research starts to become predominant, for it is necessary to obtain accurate hazard prediction in a more economical and timely manner. Making predictions based on cone calorimeter test results of representative foam and fabric combination samples became the new focus. It is important however that CBUF studies are conducted in each region where new or different furniture styles, constructions and foam/fabric combinations are used.

2.2 Combustion Behaviour of Upholstered furniture (CBUF)

The CBUF (Sundstrom 1995) research program was set up to develop methods for measuring the burning behaviour of upholstered furniture. This was in response to European fire statistics showing that the majority of fire deaths were due to fires in upholstered furniture and for the possible implementation of EU legislation and standardisation. The CBUF program consisted of the development of fire test procedures and mathematical fire models to predict important aspects of a room fire atmosphere. This was based on small-scale tests on furniture composites or individual components and validated through full-scale tests.

The Furniture Calorimeter (NT FIRE 032) was used for the testing of full-scale furniture items, while the Cone Calorimeter (ISO 5660) was used for small-scale testing of furniture components. The CBUF research program was a joint research effort conducted by over 11 different laboratories throughout Europe. For this reason strict test protocols had to be adopted, which resulted in inter-laboratory calibrations showing entirely satisfactory precision of the test methods.

Predictions based on the results of testing in the Furniture Calorimeter and use of zone (FAST) and field (JASMINE) models were made on the conditions inside two different room scenarios due to the burning of furniture items. The results of the Furniture Calorimeter tests were in turn predicted based on the results from the Cone Calorimeter tests on the furniture composite samples. Three different furniture fire models were developed and validated for achieving this prediction framework.

A special model for predicting the Cone Calorimeter (ISO 5660) test data on composites was developed; this was achieved through the testing of the individual composite component materials, ie. fabric, interliner and padding.

The test samples selected were representative of what was currently thought to characterise the large spectrum of European upholstered furniture. Burning behaviour varied from developing fire very rapidly to no combustion at all. Fabric and foam combinations were identified which gave improved fire resistance. The results of the Calorimeter tests are compiled in a FDMS standard database and contain more than 1500 tests on furniture items and its component materials

3 SCOPE OF WORK

The previous available studies, while establishing a broad data base for judging the full scale flaming combustion of upholstered chairs and elucidating some important variables, still require additional validation work to be done to reinforce and elaborate these findings. This is especially important for making an accurate hazard assessment of the furniture most typically found in that country. From studies recently conducted in New Zealand (Enright & Fleischmann 1998) it has been shown that New Zealand furniture exhibits typically higher heat release rates than those predicted by CBUF. It is the intent of this work to validate the CBUF model for the furniture specimens tested. Although the furniture specimens all conformed to the same Nordtest sofa style, they were modified in construction materials (foams and fabric covers) and from one to three seater sofas.

From these tests it is envisaged that the CBUF model will be shown to be applicable to this type of furniture and recommendations can be made for safer furniture construction based on foam and fabric choice.

4 EXPERIMENTAL FACILITIES, INSTRUMENTATION AND PROCEDURE

The data used in this research report has been tested in two different fire-testing laboratories. These were located at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the University of Canterbury (UC). The experimental set-up and procedures of both will be presented briefly below.

4.1 CSIRO facilities

This laboratory conducted all of the Furniture Calorimeter tests and just over half of the Cone Calorimeter tests.

4.1.1.1 Background

In March 1993 at the CSIRO test facilities in Melbourne a series of full scale and bench scale tests were conducted on the burning behaviour of a sofa. For the full-scale tests the sofa design conformed to the Swedish Nordtest standard, and was of metal frame design, (**fig D1** in the appendix). These tests were conducted with a variety of cushion arrangements, the configurations of which are shown in **appendix C**. In addition to this the cushions were constructed of two representative types of foams and fabric covering materials. These were *Standard Dunlop-Olympic Polyurethane* and *High Resilience Dunlop-Olympic Polyurethane* foam. The fabric covers were either 100% cellulosic (cotton/linen) or 100% thermoplastic (polypropylene). The bench-scale tests were conducted in the Cone Calorimeter on 100mm x 100mm representative foam + covering samples that the sofa was constructed from. For both the full scale and bench scale tests each cone sample or sofa cushion configuration was tested in triplicate.

Their were several objectives of these tests, the most important one was to establish a predictive model based on the cone results so that hazard analysis can be conducted just on the bench scale samples. This is in line with the research that has been conducted in the CBUF program. Unfortunately I was unable to verify that the cone samples that had been constructed and tested at CSIRO in the March of 1993, conformed to the CBUF protocol. It was thus necessary to construct my own cone samples from the original materials to the CBUF protocol and retest. These results can then be compared with those originally obtained and comparisons made. It is hoped that evidence of material ageing might be discernible. The full size tests were satisfactory, although mass loss data during the burn tests was unavailable.

4.1.2 Furniture Calorimeter

This is used to test full-scale furniture items. Measurements are made on the heat release rate using the same principle of oxygen consumption.

4.1.2.1 Test procedure

The furniture calorimeter was calibrated daily prior to any test series being conducted, using a volumetrically metered 300kW-propane burner. This allowed the gas analysis instrumentation to be calibrated. See **appendix A** for details about calibration. All specimens and ignition wood cribs were conditioned prior to the tests at 20°C and 65% RH for at least 7 days, and were tested (burnt) within 20 minutes of removal from the conditioned atmosphere. Ambient laboratory conditions (temperature, relative humidity and atmospheric pressure) were recorded 10 minutes prior to tests. Tests were pictorially recorded by videotape, with colour still photographs being taken at significant times.

The specimens were located on a cellulose-cement sheet under the centre of the smoke collection hood. The ignition crib being positioned at the centre-back of a seat cushion with one side resting against the back cushion. Data acquisition was commenced 2 minutes prior to the ignition of the crib to establish a baseline. The specimens were individually tested in the furniture calorimeter. No other combustibles except for the ignition source (wood crib) were used. The crib was then ignited on three sides with the specimen ignition time being initialised from when two sides of the crib had been ignited. The heat release contribution from the wood crib's characteristic curve (see **fig 4.1**) was subsequently subtracted from the total heat release obtained from the test. A total of 141 tests were conducted, using primarily two types of foam and two types of fabric. A schedule of the tests is given in **appendix D.** Each cushion arrangement was tested in triplicate to determine reproducibility and the likely distribution of its heat release.

4.1.2.2 Ignition source

The ignition source (Dowling & Ramsay 1983), used was a standardised 400g weight CSIRO timber crib. The crib is a cross pile of timber (*Pinus radiata*) sticks of density 500 kgm^{-3}, with dimensions being 6mm square by 200mm long. They are cut with a fine-tooth circular saw and are conditioned for a minimum of 7 days at 20°C and 65% RH, prior to being used. The crib is constructed *in situ* by building cross-piles of evenly spaced sticks. For the 400g crib the number of sticks per layer is 11. The crib is placed against the back cushion and ignited with a gas torch on its three exposed sides See **appendix C** (protocol for assessment of fire behaviour of furniture using large ignition sources - CSIRO). The heat release rate curve for the 400g crib is shown below in **fig 4.1**. This curve was subtracted from the HRR curve of each furniture item, to obtain its' accurate HRR.

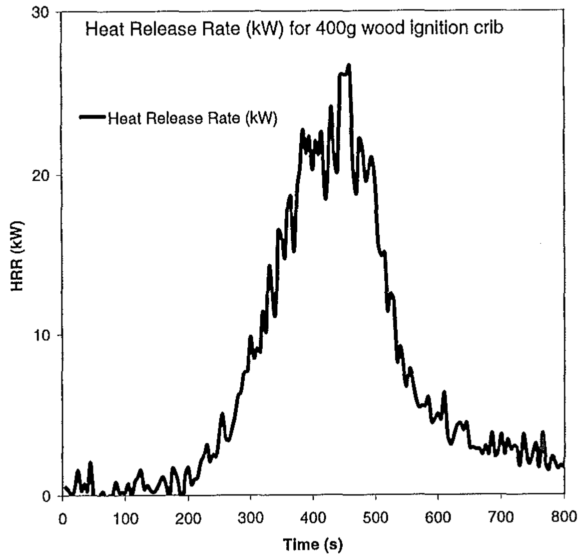

Figure 4.1 shows the characteristic heat release rate from the 400g wood ignition crib. The 400g wood crib was used for all the Furniture Calorimeter tests.

It is important to note that the above HRR curve for the 400g ignition crib is for a free burn situation, without any other combustibles present. In the situations where it is igniting and contributing to the combustion reaction of another furniture specimen its' HRR will be higher due to the increased heat flux it receives, from the now burning furniture. This is too hard to accurately predict and in any case its contribution to the total HRR is very small, and can therefore be ignored. **Fig 4.2** below shows the total energy released by the 400g wood ignition crib. This is in most cases only a fraction of a percent of the total energy released from a furniture specimen, which can range between 10 – 200MJ.

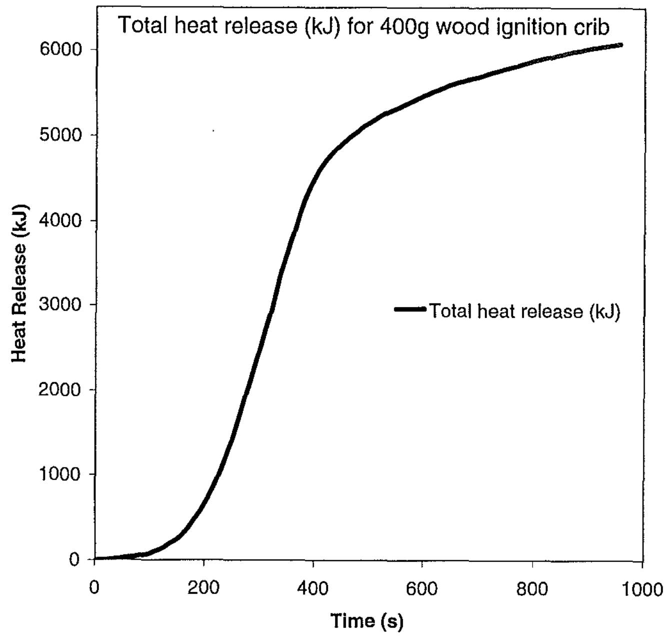

Figure 4.2 shows the total heat released from the 400g wood ignition crib

4.1.2.3 Ventilation conditions

Due to the nature of construction and size of the building in which the furniture burns were conducted in, building leakage provided the bulk of the make-up air necessary for free burning of the specimen to occur. However there was in addition to building leakage an attic door, leading to the outside, left open during all tests. During tests it was noticed that flame direction was biased quite noticeably to the right. This was most likely due to dominant draughts coming through the edges of the large garage door on the test area's left

4.1.2.4 Description of test specimens

The furniture specimens were constructed from 560 x 560 x 100mm blocks of foam, that were covered with fabric. For ease of assembly the fabric covers were cut and constructed on site, with the loose ends being joined together with light duty staples along hidden seams. Each specimen was individually tested in the CSIRO Furniture Calorimeter. No other combustibles except for the ignition crib (400g) were used. The cushions were arranged on a steel sofa frame so as to resemble chair (or part of chair) configurations. These configurations are shown in **Appendix D (fig D1)**. When only seat or back cushions were tested, a concrete fibreboard was placed where the absent cushions would have been to keep the ventilation conditions the same. The sofa frame design conformed to the Swedish Nordtest standard, being wholly constructed of steel, it was non-combustible and was used for all of the furniture calorimeter burn tests, **Appendix D (fig D2)**. The cushions were constructed from polyurethane foam, being either a *Standardgrade(Dunlop-Olympic A23-130)* or a *High Resiliencegrade (Dunlop-Olympic HR32-80)*. The nominal densities of these foams were 23 and 32kgm^{-2} respectively. The covers were either a 100% cotton/linen blend (Jacka-Wortly Valewood, 0.30kgm^{-2}) or 100% polypropylene (Jacka-Wortly Java, 0.35kgm^{-2}). Due to the ease of construction of the cushions it was possible to obtain accurate weights for both of its components. **Table 4.1** overleaf gives a complete description of the test specimens.

Cushion configuration	Single seat sofa			
Cushion construction	Standard foam + polypropylene cover			
Specimen/Test number	**FC66**	**FC68**	**FC70**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.51	0.52	0.52	0.52
Weight of foam (kg)	1.49	1.43	1.51	1.48
Total weight of cushion (kg)	2	1.95	2.03	1.99

Cushion configuration	Single seat sofa			
Cushion construction	Standard foam + cotton/linen cover			
Specimen/Test number	**FC65**	**FC67**	**FC69**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.38	0.38	0.36	0.37
Weight of foam (kg)	1.51	1.53	1.48	1.51
Total weight of cushion (kg)	1.89	1.91	1.84	1.88

Cushion configuration	Single seat sofa			
Cushion construction	High resilience foam + polypropylene cover			
Specimen/Test number	**FC75**	**FC76**	**FC78**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.52	0.51	0.5	0.51
Weight of foam (kg)	2.13	2.14	2.15	2.14
Total weight of cushion (kg)	2.65	2.65	2.65	2.65

Cushion configuration	Single seat sofa			
Cushion construction	High resilience foam + cotton/linen cover			
Specimen/Test number	**FC71**	**FC72**	**FC73**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.37	0.37	0.37	0.37
Weight of foam (kg)	2.10	2.15	2.09	2.11
Total weight of cushion (kg)	2.47	2.52	2.46	2.48

Cushion configuration	Two seat sofa			
Cushion construction	Standard foam + polypropylene cover			
Specimen/Test number	**FC28**	**FC31**	**FC33**	**Average of all three (kg)**
Weight of fabric cover (kg)	1.06	1.06	1.10	1.07
Weight of foam (kg)	3.03	3.03	2.99	3.02
Total weight of cushion (kg)	4.09	4.09	4.09	4.09

Cushion configuration	Two seat sofa			
Cushion construction	Standard foam + cotton/linen cover			
Specimen/Test number	**FC29**	**FC30**	**FC32**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.75	0.79	0.77	0.77
Weight of foam (kg)	3.03	3.01	2.92	2.99
Total weight of cushion (kg)	3.78	3.80	3.69	3.76

Cushion configuration	Two seat sofa			
Cushion construction	High resilience foam + polypropylene cover			
Specimen/Test number	**FC35**	**FC36**	**FC39**	**Average of all three (kg)**
Weight of fabric cover (kg)	1.08	1.04	1.04	1.05
Weight of foam (kg)	4.25	4.29	4.17	4.24
Total weight of cushion (kg)	5.33	5.33	5.21	5.29

Cushion configuration	Two seat sofa			
Cushion construction	High resilience foam + cotton/linen cover			
Specimen/Test number	**FC34**	**FC37**	**FC38**	**Average of all three (kg)**
Weight of fabric cover (kg)	0.75	0.75	0.76	0.75
Weight of foam (kg)	4.12	4.22	4.32	4.22
Total weight of cushion (kg)	4.87	4.97	5.08	4.97

Cushion configuration	Three seat sofa			
Cushion construction	Standard foam + polypropylene cover			
Specimen/Test number	FC139	FC140	FC141	Average of all three (kg)
Weight of fabric cover (kg)	1.46	1.47	1.47	1.47
Weight of foam (kg)	4.83	4.52	4.38	4.58
Total weight of cushion (kg)	6.29	5.99	5.85	6.04

Cushion configuration	Three seat sofa			
Cushion construction	Standard foam + cotton/linen cover			
Specimen/Test number	FC136	FC137	FC138	Average of all three (kg)
Weight of fabric cover (kg)	1.19	1.09	1.07	1.12
Weight of foam (kg)	4.38	4.44	4.47	4.43
Total weight of cushion (kg)	5.57	5.53	5.54	5.55

Cushion configuration	Three seat sofa			
Cushion construction	High resilience foam + polypropylene cover			
Specimen/Test number	FC135	-	-	Average of all three (kg)
Weight of fabric cover (kg)	1.53	0	0	1.53
Weight of foam (kg)	6.39	0	0	6.39
Total weight of cushion (kg)	7.92	0	0	7.92

Cushion configuration	Three seat sofa			
Cushion construction	High resilience foam + cotton/linen cover			
Specimen/Test number	FC142	FC143	FC144	Average of all three (kg)
Weight of fabric cover (kg)	1.10	1.09	1.07	1.09
Weight of foam (kg)	6.20	6.30	6.17	6.22
Total weight of cushion (kg)	7.30	7.39	7.24	7.31

Table 4.1 summarises the construction and weight details of the furniture specimens

4.1.2.5 Configuration of furniture calorimeter

The furniture calorimeter is situated in a large open room of approximately 170m^2 with the burn test site backed on one side by an internal brick wall. Building leakage and the opening of a rear interior door during tests provides the make-up air, sufficient for complete combustion. This set-up provides the required air yet in a relatively unbiased draught environment. The smoke collection hood is of steel construction in the form of a truncated right pyramid, with bottom edge dimensions of 3m x 3m and a height of 1m. Sheet steel sides extend downward from the hood for a further 1m. The top of the hood feeds in to a plenum with dimensions of 0.9 x 0.9 x 0.9 metres. An exhaust duct connects the plenum to an exhaust fan and gas-fired afterburner, which removes harmful combustion products before releasing the exhaust gases into the outside atmosphere. The duct contains instrumentation for measuring the flow rate and temperature of the exhaust gases, an optical smoke measurement system to determine optical density of the combustion gases and a gas-sampling probe. The smoke collection hood and exhaust system meets the specifications as listed in the Nordtest Standard (NT Fire 032). **Fig 4.3** shows diagrammatically the burn room set-up and hood/smoke exhaust arrangement.

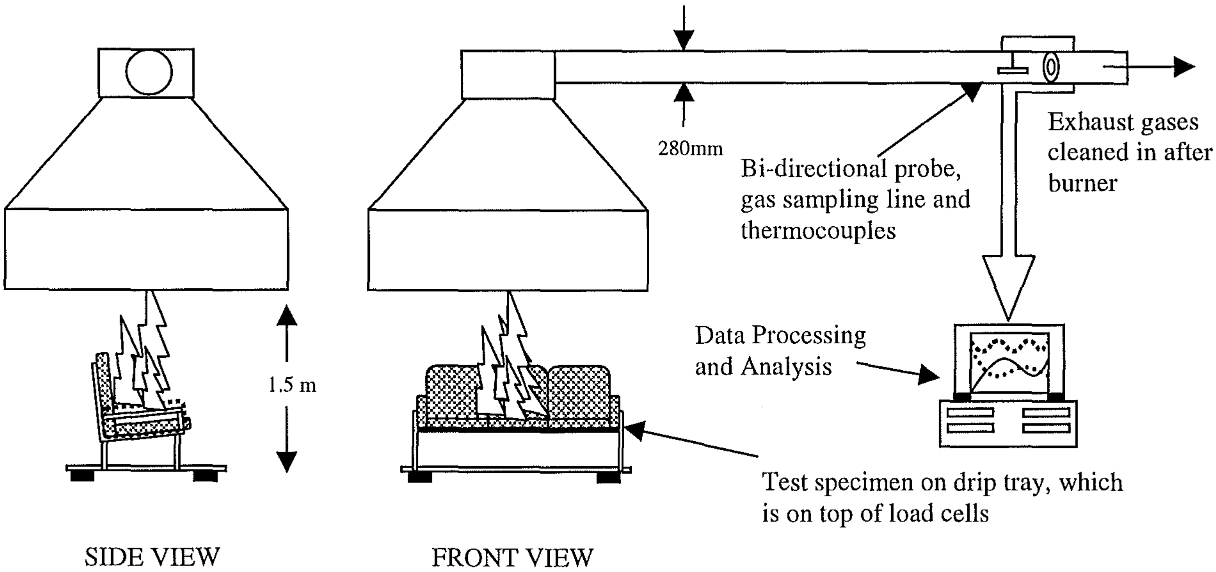

Figure 4.3 shows the Furniture Calorimeter layout at CSIRO for which all specimens were tested

4.1.2.6 Measurement of heat release

The heat release rate is measured by oxygen consumption calorimetry, using Huggett's principle. To do this it is necessary to collect and accurately measure the concentrations of oxygen, carbon monoxide and carbon dioxide in the exhaust gases. A hood mounted directly over the specimen collected the combustion gases. As they travelled down this exhaust duct a sample was continuously extracted (recorded every 5 seconds) and passed through a series of analysers. As this sampling point was located sufficiently downwind of the collection hood it was assumed that the exhaust gases were well mixed (this is most important as the sample must be representative of the exhaust gases at that instant). The Oxygen concentration was measured using a *Servomex 570A* analyser, while the CO and CO_2 concentrations were measured with a *Horiba PIR 2000* analyser. The exhaust gas temperature was also measured at this sample point, using a pair of *type K* thermocouples. The speed of the exhaust gases was measured via a bi-directional probe connected to a *Setra Datum 2000* micromanometer. The above data enabled the heat release rates from the burning specimens to be calculated via oxygen consumption calorimetry calculations. It is important to note that there is a time delay between the actual heat release and when it was being measured. This is due to the time lag associated with the gas analysis procedures and will be discussed in greater detail later in this report. The instrumentation in the duct also met the specifications given in the Nordtest Standard (NT Fire 032).

4.1.3 Cone calorimeter

4.1.3.1 Test procedure

The cone calorimeter was calibrated daily prior to any test being conducted by a volumetrically metered 30kW-propane burner. This allowed the gas analysis instrumentation to be calibrated. All cone specimens were conditioned prior to the tests at 20°C and 65% RH for at least 7 days, and were tested (burnt) within 5 minutes of removal from the conditioned atmosphere. Ambient laboratory conditions (temperature, relative humidity and atmospheric pressure) were recorded 10 minutes prior to tests.

Each foam and fabric combination was tested in triplicate to determine repeatibility and the likely range or distribution of its peak and total heat release.

Delay times in the gas analyser sample train for the O_2, CO and CO_2 measurements were (14), 18, 11 and 12 seconds respectively. The O_2 analyser pipeline was re-routed after the 35kW heat flux tests and now records a delay lag time of 18 seconds.

4.1.3.2 Ignition source

The ignition source used was a spark gap igniter, which is located just 10mm above the cone sample. The cone sample was irradiated with either a 25kW or 35kW heater element, again located just above the sample but arranged in the shape of a truncated cone so that combustion gases could pass through it to be collected and analysed.

4.1.3.3 Description of test specimens

The CSIRO cone samples were constructed from foam and fabric representative of the furniture that was tested in the CSIRO Furniture Calorimeter. They were constructed from 100mm x 100mm x 50mm thick blocks of foam, covered by a 200mm x 200mm square of fabric. The overlapping fabric was folded over the sides on the diagonal and stapled together at the bottom edge. The cone samples were constructed of 100mm x 100mm x 50mm thick blocks of foam (either *Standard* or *High Resilience Dunlop-Olympic Polyurethane* foam) covered with either the polypropylene or cotton/linen fabric. The fabric was cut into a 200mm x 200mm square, then fitted over the foam block. Unfortunately only the total weight was recorded so the weights of the individual fabric and foam components can only be approximated. The construction weights and test details for these specimens are shown below in **Table 4.2**. For further details see **appendix F**.

Cone sample construction	Standard foam + polypropylene fabric cover					
Cone sample test	PU&C36A	PU&C36B	PU&C36C	PU&C36D	PU&C36E	PU&C36F
Total weight (g)	19.8	20.2	20.6	20.2	20.3	20.0
Irradiance level (kW)	35	35	35	25	25	25

Cone sample construction	High resilience foam + polypropylene fabric cover					
Cone sample test	PU&C37A	PU&C37B	PU&C37C	PU&C37D	PU&C37E	PU&C37F
Total weight (g)	24.6	27.2	26.0	26.8	26.3	26.7
Irradiance level (kW)	35	35	35	25	25	25

Cone sample construction	Standard foam + cotton/linen fabric cover					
Cone sample test	PU&C38A	PU&C38B	PU&C38C	PU&C38D	PU&C38E	PU&C38F
Total weight (g)	18.1	17.6	18.0	18.7	19.3	17.0
Irradiance level (kW)	35	35	35	25	25	25

Cone sample construction	High resilience foam + cotton/linen fabric cover					
Cone sample test	PU&C39A	PU&C39B	PU&C39C	PU&C39D	PU&C39E	PU&C39F
Total weight (g)	23.6	23.8	22.4	24.3	21.8	22.8
Irradiance level (kW)	35	35	35	25	25	25

Table 4.2 shows the masses, heat fluxes and construction materials of the cone tests samples

4.2 University of Canterbury facilities

The Cone Calorimeter facilities are very similar to those at CSIRO, both use *the Stanton Redcroft* Cone Calorimeter Apparatus. The most noticeable difference is in the use of different gas analysers (*Servomex 540A* for measuring oxygen and the *Siemens Ultramat 6* for measuring CO and CO_2). The delay lag times in the exhaust gas sample train, for the O_2, CO and CO_2 measurements are 4, 1 and 1 seconds respectively. However, these delays do not include the transport lag times. For a full description and discussion of the University of Canterbury's Cone Calorimeter see (Enright 1999).

5 TEST SPECIMEN PROGRAM

5.1 Furniture Calorimeter

Each cushion configuration was tested in triplicate and given an alphanumeric code and test number for future reference. A total of 141 tests were conducted, using one steel sofa frame, 11 different cushion combinations, four different foams and two different fabrics. The ignition source was the CSIRO standardised 400g wood crib. A schedule of tests is given in **appendix E**. These tests were commenced on the 18th March 1993 and concluded on the 30th December that same year.

5.2 Cone Calorimeter

Two different fabrics and foams samples were tested in triplicate at both 25kWm^{-2} and 35kWm^{-2} irradiances, making a total of 24 individual tests. They were tested in the CSIRO Cone Calorimeter in their aluminium foil holder, (without the edge frame), thus the specimen exposure area was 0.01m^2. Each individual test was prescribed a code for future reference. A schedule of these tests is given in **appendix F**, and was conducted at CSIRO during the months of February and March 1993.

An additional series of tests were conducted in December 1998 on the High Resilience foam/polypropylene fabric series at irradiances of 15, 25 and 35kWm^{-2}. These were constructed and tested according to the AS/NZS 3837:1998 protocol. Each irradiance level was tested in triplicate, which gave a total of 9 individual tests. An edge frame was used giving a specimen exposure area of 0.0088m^2. A schedule for these tests is also shown in **appendix F**.

Due to strict CBUF protocols requiring stringent adherence to their required specimen preparation method, the original test series, using the original foams and fabrics were reconstructed to CBUF's guidelines and tested on the Canterbury University Cone Calorimeter in February 1999. No edge frame was used around the specimen (exposure area was 0.01m^2) and the Cone irradiance was 35kWm^{-2}. A full schedule of these tests is given in **appendix G**.

6 CRITERIA FOR EVALUATION

The full-scale raw data (Furniture Calorimeter tests) was processed using Janssens equations to yield their HRR curves, peak HRR, time to reach peak HRR and total heat released. This was conducted via a spreadsheet program (Microsoft Excel 97), with only the above results included, for clarity.

The small-scale raw data (Cone Calorimeter tests) was also processed in this way but additional data, such as the HRR curve characteristics (1^{st} & 2^{nd} peaks, HRR trough) and time to reach these points will be recorded, in tabular form. From these results a predictive model will be used to scale these results up to the full-scale. The HRR characteristics are defined from the CBUF report as shown in **fig 6.1** below.

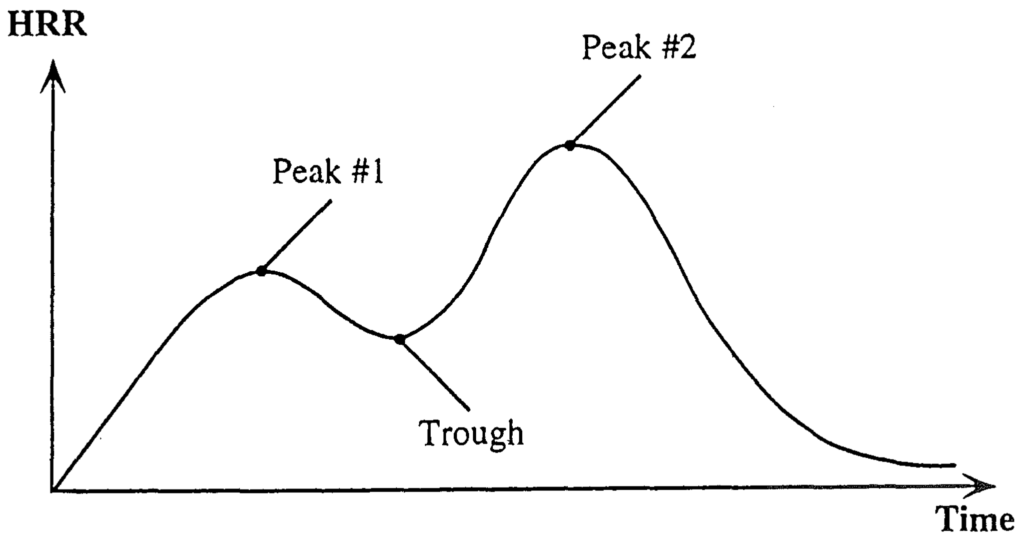

Figure 6.1 shows the schematic view of a Cone Calorimeter HRR curve. The particular characteristics used in *Model I* have been labelled.

6.1 Predictive modelling of the combustion behaviour of upholstered furniture

Full-scale fire testing is much more costly, time consuming and unwieldy than bench-scale testing. Thus one of the main objectives of modern fire research is to improve bench-scale based predictive models of full-scale behaviour. Currently models have been developed that predict not just the free burning behaviour of an upholstered specimen, but also its combustion behaviour inside a standard compartment,(Sundstrom 1995). The reaction property of most interest is the Heat Release Rate (HRR), as it is from this that most other fire properties are derived. The HRR describes the size of the fire reaction. The Cone Calorimeter is the most recognised and currently accepted apparatus for conducting bench-scale tests. A bench-scale predictive model, based on the Cone Calorimeter was first developed at the National Bureau of Standards, (Babrauskas1982). However this predictive model was based mainly on materials and furniture specimens originating prior to the 1980's. Since that time furniture has become constructed of increasingly more flammable materials. Although the predictive models have also changed to keep pace with the changing construction of furniture it is still necessary to validate these predictive models, especially when examining furniture that has been constructed outside of the model.

In 1993 the European Commission sponsored the CBUF (Combustion Behaviour of Upholstered Furniture) program, the results from this were published in 1995. They tested a large sample of representative modern European furnishings. Three predictive combustion behaviour models were developed from these results:

Model I-	Correlation based
Model II-	Area convolution based
Model III-	Extension of a thermal flame spread model.

6.1.1 CBUF predictive fire model I

This model is based upon correlation formulas that are 'factor' based. These 'factors' are obtained from statistical data derived from the type of furniture that is being modelled. They are used to predict the following parameters of the burning specimen:

- peak heat release rate
- time to reach peak HRR
- total energy release
- smoke production
- time to reach untenability in the standard compartment

The correlations are validated against the CBUF database. It is important that it be determined whether the fire will be propagating or non-propagating, as non-propagating fires are assumed to not occur. The Cone Calorimeter HRR (average value taken over 180 seconds, after specimen ignition under an irradiance of $35kWm^{-2}$) can be used to determine whether a furniture fire will be propagating or not. The CBUF work concluded that this limiting value was 65kWm^{-2} (this value best fitted experimental data).

6.1.1.1 Prediction of peak heat release rate

To predict the peak HRR, ***Q*** it is necessary to make use of the **Equations 1 - 5** listed below. These have been derived from statistical analysis of the results in the CBUF database. The results from the CBUF study are shown in **fig 6.2** below.

$$x_1 = (m_{soft})^{1.25}(style\_fac.A)(q''_{peak} + q''_{300})^{0.7}(15 + t_{ig})^{-0.7} \qquad \textbf{[Equation 1]}$$

$$x_2 = 880 + 500(m_{soft})^{0.7}(style\_fac.A)\left(\frac{\Delta h_{c,eff}}{q''_{total}}\right)^{1.4} \qquad \textbf{[Equation 2]}$$

Selection rules have been established, that I have termed **'regimes'**, to determine which correlating variable (x_1 or x_2 above) is to be used. These are listed below. The dependence on the correlating variables will be discussed further in the **analysis of results** section.

REGIME 1

If (x_1>115) or (q_{total}''> 70 and x_1>40) or (*style code* = {3,4} and x_1>70), then

$$Q = x_2 \qquad \textbf{[Equation 3]}$$

Else,

REGIME 2

If $x_1 < 56$, then

$$Q = 14.4x_1 \qquad \textbf{[Equation 4]}$$

Else,

REGIME 3

$$Q = 600 + 3.77x_1 \qquad \textbf{[Equation 5]}$$

6.1.1.2 Total heat release, Q

The total heat release is a measure of the effective fire load from the furniture item. **Equation 6** below was found to represent the total heat release to a high degree of accuracy. The results of the CBUF study are shown in **fig 6.3** below.

$$Q = 0.9 m_{soft} \Delta h_{c,eff} + 2.1 \left[m_{total\_combustible} - m_{soft} \right]^{1.5}$$ **[Equation 6]**

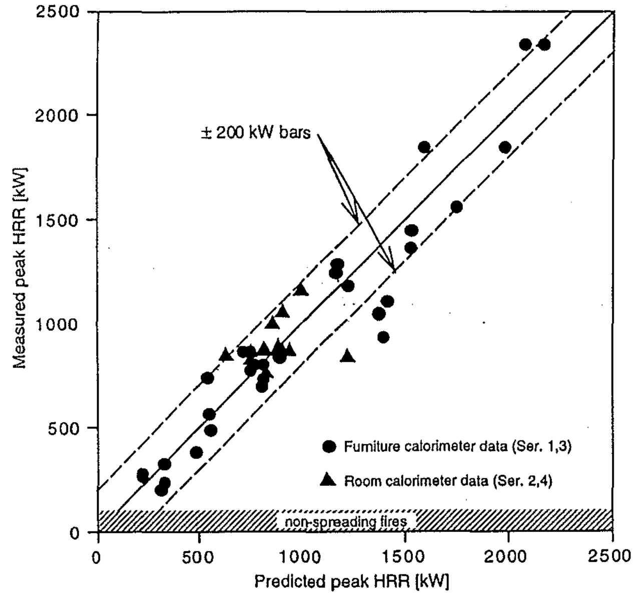

Figure 6.2 shows the CBUF results for the prediction of peak HRR using Model I for propagating upholstered furniture fires.

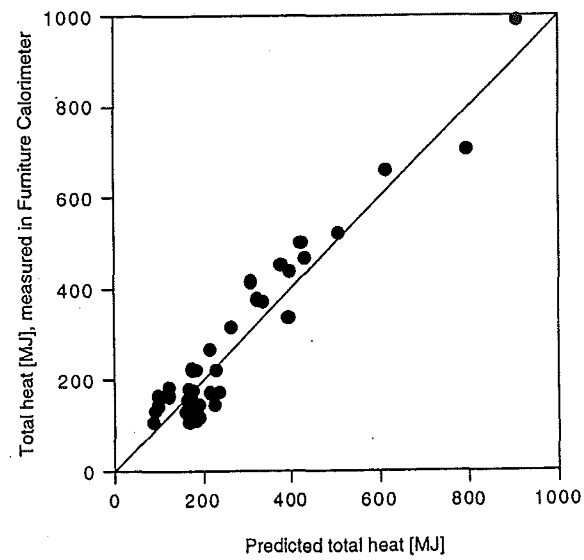

Figure 6.3 shows Model I's prediction of the total heat released based on CSIRO's results.

6.1.1.3 Time to peak heat release rate, t_{pk}

The time to peak HRR is taken as the time from 'sustained burning', (this is defined at the HRR level of $50kWm^{-2}$) to the time that maximum HRR is reached; **Equation 7** below gives the predicted result. Due to the differences in ignition source used between the CSIRO and CBUF Furniture Calorimeter tests, these predictions will be the least reliable

$$t_{pk} = 30 + 4900(style\_fac.B)(m_{soft})^{0.3}(q''_{pk\#2})^{-0.5}(q''_{trough})^{-0.5}(t_{pk\#1} + 200)^{0.2}$$

[Equation 7]

6.1.1.4 Time to untenability, t_{UT}

The time to untenability is taken from the time at which the level is 50kWm^{-2} (sustained burning) to when a temperature of 100 ^{0}C is reached in the upper layer (at 1.1 to 2.1 metres above floor level). This is for the ISO standard room; (dimensions 3.6 x 2.4 x 2.4m, with a door in the centre of one of the 2.4 x 2.4m walls. The door measures 2.0 x 0.8m). **Equation 8** below defines this parameter. CBUF results are shown in **fig 6.3.**

$$t_{UT} = 1.5 \times 10^5(style\_fac.B)(m_{soft})^{-0.6}(q''_{trough})^{-0.8}(q''_{pk\#2})^{-0.5}(t_{pk\#1} - 10)^{0.15}$$

[Equation 8]

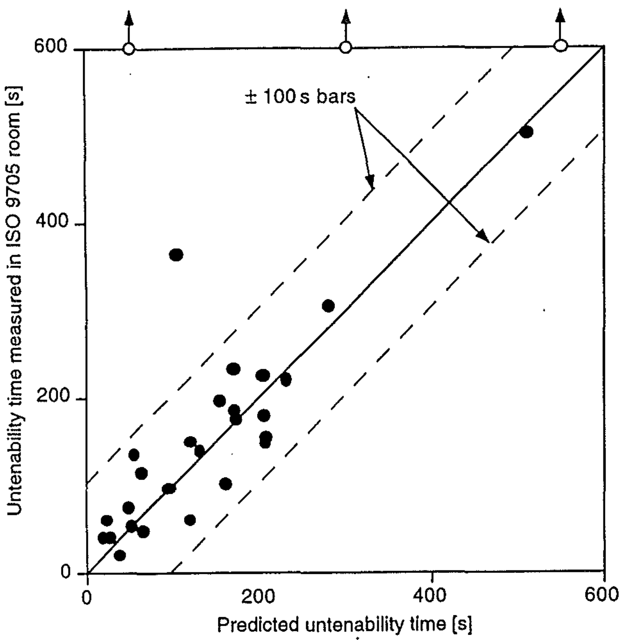

Figure 6.4 shoes Model I's prediction of time to untenability base on CBUF's test results

6.1.1.5 Smoke modelling

The following correlations (**Equations 9 - 13**) were established for predicting the smoke production from the burning specimen, this was for propagating fires, and excluded mattresses, beds and chairs with hard plastic parts. As can be seen from **fig 6.5** these correlations give very good agreement for fires showing moderate smoke production (less than 1500m^2). For fires with seriously large smoke production values the predicted values are either very close or higher than the actual measurements, thus making the model a conservative estimate under all circumstances. The equations below are based primarily on the HRR as it has been shown to be the fundamental variable of the fire. It has been found from Cone Calorimeter however, that this is not a linear dependence. For higher HRR, the smoke production in the Cone is slightly less than full-scale results and vice versa.

The smoke production equations are as follows:

$$p_1 = 0.7\left(\frac{Q_{total}\sigma_f}{\Delta h_{c,eff}}\right)$$ **[Equation 9]**

$$p_2 = s_o - 0.15 s_o^{1.13} \textbf{ with } s_o = \frac{Q_{total}\sigma_f\left(1.25 - 0.00188 q''_{35-60}\right)}{\Delta h_{c,eff}}$$ **[Equations 10 & 11]**

If $p_2 < 1800$ then,

$$SmP = p_2$$ **[Equation 12]**

Else,

$$SmP = p_1$$ **[Equation 13]**

Where

$\boldsymbol{SmP}$	=	full-scale smoke production [m^2]
Q_{total}	=	full-scale total heat release [MJ]
σ_f	=	Cone Calorimeter average specific extinction area [m^2kg^{-1}]
$\Delta h_{c,eff}$	=	Cone calorimeter average effective heat of combustion [$MJkg^{-1}$]
q_{35-60}''	=	the 60 second average HRR value from the Cone Calorimeter [kWm^{-2}]
q_{trough}''	=	HRR in the Cone Calorimeter at the trough following the 1st peak [kWm^{-2}]
q_{pk}''	=	peak HRR at 35kWm^{-2} exposure [kWm^{-2}]
$q_{pk\#2}''$	=	HRR at the 2nd peak [kWm^{-2}]
q_{300}''	=	300 second average HRR [kWm^{-2}] at 35kWm^{-2} exposure [kWm^{-2}]
q_{total}''	=	total heat release at 35kWm^{-2} exposure [$MJkg^{-1}$]
$t_{pk\#1}$	=	time to the 1st peak [s]
t_{ig}	=	ignition time at 35kWm^{-2} exposure [s]

m_{soft} = mass of soft upholstery (fabric, filling, interliner etc.) materials [kg]

$m_{total\_combustible}$ = mass of entire upholstery combustible (fabric, filling, interliner, combustible frame etc.) materials [kg]

Style_fac.A = this is a statistical factor as defined in **Table 6.1** [--]

Style_fac.B = this is a statistical factor as defined in **Table 6.1** [--]

Style code	Style factor A	Style factor B	Type of furniture
1	1.0	1.0	Armchair, fully upholstered, average amount of padding
2	1.0	0.8	Sofa, 2seater
3	0.8	0.8	Sofa, 3 seater
4	0.9	0.9	Armchair, fully upholstered, highly padded
5	1.2	0.8	Armchair, small amount of padding
6	1.0	2.5	Wingback chair
-	-	-	Mattresses
12	0.6	0.75	Sofa-bed (convertible)
13	1.0	0.8	Armchair, fully upholstered, metal frame
14	1.0	0.75	Armless chair, seat and back cushions only
15	1.0	1.0	Armless 2 seater sofa, seat and back cushions only

Table 6.1 shows the style factors that pertain to the different types of furniture, used in the CBUF study. This table has omitted several furniture classifications dealing with mattresses and office chairs that are outside the scope of this report.

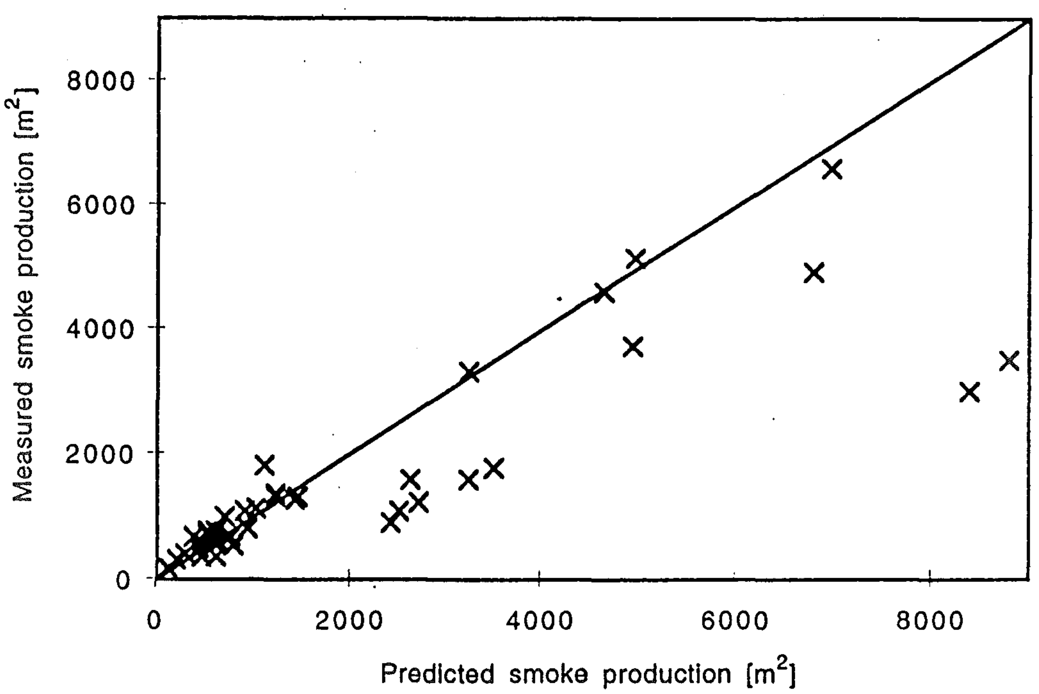

Figure 6.5 shows the comparison of predicted smoke production against full-scale data obtained from the Furniture Calorimeter in the CBUF study.

6.1.2 Choosing a starting time for CBUF criteria

As a (400g) wood ignition crib was used to ignite the full-scale furniture specimens, ignition characteristics become substantial. To try to eliminate or reduce the effect that this contributes to the combustion behaviour of the furniture specimens I have time shifted the HRR curves so that their leading HRR edges coincide. This was necessary so that direct visual comparisons could be made. Furthermore it is necessary due to these ignition characteristics to choose a starting heat release rate upon which *time to peak HRR*, and *time to reach untenability* criteria can be based. This is not an easy number to arise at with justification, except to say that the purposes of this report is to study the burning behaviour of furniture, with the special intention of being able to apply *CBUF - model I* to the results. The starting ignition characteristics are not included in the analysis of the burning behaviour of furniture, as they are too hard to adequately quantify and predict. For this reason the *time to reach peak heat release rate* in the *CBUF model I* prediction analysis, is taken as starting from when the furniture specimens' HRR exceeds 50kW. It is important to realise that this is not an arbitrary figure but comes from current research, which states that non-propagating full-scale furniture fires experimentally exhibit peak HRR values of between 20 to 100kW, (Sundstrom 1995). The peak heat release rate for the 400g ignition crib was 30kW, however this was in isolation from any other combustibles. It is well known that in the presence of other combustibles, which would contribute considerably to the surrounding heat flux, that its' HRR could be up to 50% greater still. These findings are validated by the results achieved from the Cone Calorimeter tests, at varying heat flux irradiances.

Internationally the ignition characteristics of furniture are a hot bed of ongoing research (ignition being undoubtably the most critical determining factor of any fire hazard, but very difficult to accurately characterise, and outside of the scope of this report).

7 RESULTS

The results from both the Cone and Furniture Calorimeter tests are summarised below in tabular form. The graphical illustrations of the HRR curves and correlation results from this data are placed in the **Analysis of results section** as they are discussed more fully there.

7.1 Cone Calorimeter data

Table 7.1 below, summarises the results of the CSIRO Cone Calorimeter tests used in the CBUF *Model I.* Each sample specimen represents an actual cone test, with the predictions being based on the mean of each triplicate. It is important to note that these cone samples were not constructed according to the CBUF protocol.

	Standard Polyurethane foam + polypro						Standard Polyurethane foam + cotton					
Variable	**1**	**2**	**3**	**Mean**	**σ**	**Variation**	**1**	**2**	**3**	**Mean**	**σ**	**Variation**
m (g)	19.8	20.2	20.6	**20.2**	**0.4**	2%	18.1	17.6	18	**18**	**0.3**	1%
t_{ig} (s)	6	6	6	**6.0**	**0.0**	0%	6	6	6	**6.0**	**0.0**	0%
q" (MJ/m2)	64	66	64	**64.5**	**1**	2%	37	37	37	**37**	**0.4**	1%
q''_{60} (MJ/m2)	271	305	239	**272**	**33**	12%	153	151	135	**146**	**10**	7%
q''_{120} (MJ/m2)	340	387	339	**355**	**27**	8%	143	143	126	**137**	**10**	7%
q''_{180} (MJ/m2)	319	340	346	**335**	**14**	4%	143	152	132	**142**	**10**	7%
q''_{300} (MJ/m2)	203	213	212	**209**	**6**	3%	116	118	116	**117**	**1**	1%
$q''_{peak\ 1}$ (kW/m2)	437	498	456	**464**	**31**	7%	309	247	209	**255**	**50**	20%
$t_{peak\ 1}$ (s)	75	85	80	**80**	**5**	6%	15	15	15	**15**	**0**	0%
q''_{trough} (kW/m2)	374	-	412	**393**	**27**	7%	117	124	108	**116**	**8**	7%
t_{trough} (s)	120	-	125	**123**	**4**	3%	115	100	105	**107**	**8**	7%
$q''_{peak\ 2}$ (kW/m2)	389	-	440	**415**	**36**	9%	148	183	151	**161**	**19**	12%
$t_{peak\ 2}$ (s)	125	-	145	**135**	**14**	10%	160	155	180	**165**	**13**	8%
$\Delta h_{c,eff}$ (MJ/kg)	32.5	32.5	30.9	**32.0**	**0.9**	3%	20.3	21.6	20.7	**20.9**	**0.7**	3%

	High Resilience foam + polypropylene						High Resilience foam + cotton					
Variable	**1**	**2**	**3**	**Mean**	**σ**	**Variation**	**1**	**2**	**3**	**Mean**	**σ**	**Variation**
m (g)	24.6	27.2	26.0	**25.9**	**1.3**	5%	23.6	23.8	22.4	**23.3**	**0.8**	3%
t_{ig} (s)	6	6	6	**6.0**	**0.0**	0%	6	6	6	**6.0**	**0.0**	0%
q" (MJ/m2)	74	78	72	**74.7**	**3**	4%	48	54	46	**49**	**3.9**	8%
q''_{60} (MJ/m2)	191	191	175	**186**	**9**	5%	125	110	92	**109**	**17**	15%
q''_{120} (MJ/m2)	294	305	295	**298**	**6**	2%	95	97	89	**94**	**4**	4%
q''_{180} (MJ/m2)	312	322	316	**317**	**5**	2%	93	114	132	**113**	**20**	17%
q''_{300} (MJ/m2)	236	256	240	**244**	**11**	4%	120	150	142	**137**	**16**	11%
$q''_{peak\ 1}$ (kW/m2)	445	464	478	**462**	**17**	4%	294	216	233	**248**	**41**	17%
$t_{peak\ 1}$ (s)	100	100	100	**100**	**0**	0%	15	20	20	**18**	**3**	16%
q''_{trough} (kW/m2)	324	336	330	**330**	**6**	2%	58	75	64	**66**	**9**	13%
t_{trough} (s)	175	160	150	**162**	**13**	8%	110	45	50	**68**	**36**	53%
$q''_{peak\ 2}$ (kW/m2)	365	382	377	**375**	**9**	2%	176	294	275	**248**	**63**	26%
$t_{peak\ 2}$ (s)	195	195	185	**192**	**6**	3%	210	210	195	**205**	**9**	4%
$\Delta h_{c,eff}$ (MJ/kg)	30.2	28.5	28.1	**28.9**	**1.1**	4%	23.3	24.2	21.9	**23.1**	**1.2**	5%

Table 7.1 shows the CSIRO Cone test data with the associated variation within each test triplicate

Table 7.2 overleaf, summarises the results of the University of Canterbury Cone Calorimeter tests which will be used in *Model I.* of CBUF Each sample specimen represents an actual cone test, with the predictions being based on the mean of each triplicate

Table 7.2 shows the University of Canterbury Cone test data with the associated variation within each test triplicate

Variable	Standard Polyurethane foam						Standard Polyurethane foam + polypro						Standard Polyurethane foam + cotton					
	1	2	3	Mean	σ	Variation	1	2	3	Mean	σ	Variation	1	2	3	Mean	σ	Variation
m (g)	12.0	11.9	11.9	11.9	0.1	0%	24.6	24.5	24.7	24.6	0.1	0%	20.49	20.37	20.34	20.4	0.1	0%
t_{ig} (s)	4	6	6	5	1.2	22%	10	9	9	9.3	0.6	6%	11	11	12	11.3	0.6	5%
q'' (MJ/m2)	27	26	27	27	0.2	1%	64	65	65	64.4	0.5	1%	37	35	36	35.9	1.0	3%
q''_{60} (MJ/m2)	248	299	295	281	28	10%	315	348	344	336	18	5%	251	285	228	254.7	29	11%
q''_{120} (MJ/m2)	215	218	221	218	3	1%	347	414	390	384	34	9%	192	198	191	193.7	4	2%
q''_{180} (MJ/m2)	148	142	145	145	3	2%	341	355	349	348	7	2%	155	160	160	158.3	3	2%
q''_{300} (MJ/m2)	115	110	108	111	3	3%	292	283	290	288	5	2%	182	121	123	142.0	35	24%
$q''_{peak\ 1}$ (kW/m2)	311	419	414	381	61	16%	473	552	527	517	40	8%	349	375	347	357.0	16	4%
$t_{peak\ 1}$ (s)	64	41	43	49	13	26%	48	74	38	53	19	35%	18	15	16	16.3	2	9%
q''_{trough} (kW/m2)	224	376	326	309	77	25%	343	445	382	390	51	13%	245	313	213	257.0	51	20%
t_{trough} (s)	80	55	55	63	14	23%	92	119	69	93	25	27%	49	24	28	33.7	13	40%
$q''_{peak\ 2}$ (kW/m2)	226	385	338	316	82	26%	466	487	455	469	16	3%	261	363	252	292.0	62	21%
$t_{peak\ 2}$ (s)	82	56	60	66	14	21%	135	125	121	127	7	6%	54	42	44	46.7	6	14%
$\Delta h_{c,eff}$ (MJ/kg)	20.4	20.4	20.5	20.4	0.1	0%	25.3	26.6	26.3	26.1	0.7	3%	20.7	19.5	19.4	19.9	0.7	4%
MLR	13.1	12.9	13.1	13.0	0.1	1%	25.2	24.2	23.8	24.4	0.1	0%	17.9	15.9	16.3	16.7	1.1	6%
m'' (g/m2.s)	5.0	5.0	5.0	5.0	0.0	1%	8.3	8.2	8.3	8.3	0.7	9%	6.1	6.1	6.2	6.1	0.1	1%

Variable	High Resilience foam						High Resilience foam + polypropylene						High Resilience foam + cotton					
	1	2	3	Mean	σ	Variation	1	2	3	Mean	σ	Variation	1	2	3	Mean	σ	Variation
m (g)	16.8	16.8	16.8	16.8	0.0	0%	29.0	28.9	29.1	29.0	0.1	0%	23.7	23.8	23.6	23.7	0.1	0%
t_{ig} (s)	3	5	3	4	1	31%	9	16	11	12.0	3.6	30%	12	12	11	11.7	0.6	5%
q'' (MJ/m2)	36	36	36	36	0	1%	73	76	74	74.3	1.3	2%	37	39	40	39	1.7	4%
q''_{60} (MJ/m2)	189	174	187	183	8	5%	245	320	291	285	38	13%	158	153	140	150	9	6%
q''_{120} (MJ/m2)	234	229	260	241	17	7%	350	415	372	379	33	9%	149	142	158	150	8	5%
q''_{180} (MJ/m2)	196	192	211	200	10	5%	375	404	391	390	15	4%	155	156	169	160	8	5%
q''_{300} (MJ/m2)	196	157	211	188	28	15%	251	265	255	257	7	3%	128	134	135	132	4	3%
$q''_{peak\ 1}$ (kW/m2)	315	328	392	345	41	12%	591	567	506	555	44	8%	280	284	294	286	7	3%
$t_{peak\ 1}$ (s)	58	68	57	61	6	10%	98	69	54	74	22	30%	10	10	13	11	2	16%
q''_{trough} (kW/m2)	276	271	340	296	38	13%	427	461	438	442	17	4%	111	97	130	113	17	15%
t_{trough} (s)	81	85	71	79	7	9%	129	98	79	102	25	25%	71	83	75	76	6	8%
$q''_{peak\ 2}$ (kW/m2)	299	328	392	340	48	14%	492	547	509	516	28	5%	190	197	239	209	27	13%
$t_{peak\ 2}$ (s)	103	94	79	92	12	13%	143	123	124	130	11	9%	129	134	125	129	5	3%
$\Delta h_{c,eff}$ (MJ/kg)	20.1	22.3	20.5	20.9	1.1	5%	27.3	28.4	27.5	27.7	0.6	2%	18.8	19.4	19.4	19.2	0.3	2%
MLR	17.7	16.1	17.6	17.1	0.9	5%	26.8	26.7	27.0	26.8	0.2	1%	19.6	19.8	20.8	20.1	0.6	3%
m'' (g/m2.s)	5.9	6.0	6.0	6.0	0.0	1%	9.1	9.1	9.2	9.1	0.1	1%	6.7	6.8	7.0	6.8	0.2	2%

For the purposes of comparison and to allow a visual approximation of the relative uncertainty, the associated standard deviation and variation are recorded for each measured parameter within the triplicate series. Here variation is defined as the percentage value of the standard deviation divided by the mean. These cone samples were constructed according to the procedure as defined in the CBUF report.

Table 7.3 summarises the auxiliary data required by the CBUF predictive model. This data relates to the combustible mass and style of the full-scale furniture specimens. The style of the specimens were exactly the same (Nordtest sofa frame) except for being one, two or three seaters. It is interesting that the CBUF model doesn't take into consideration fabric effects in any of the correlation equations.

Because only the cushions are combustible here $\mathbf{m_{soft}} = \mathbf{m_{combustible}}$.

	furniture specimen	msoft (kg)	style code (--)	style_fac.A (--)	style_fac.B (--)
HR foam + cotton/linen	fc71	2.47	14	1.0	0.75
	fc72	2.52	14	1.0	0.75
	fc73	2.46	14	1.0	0.75
	fc34	4.87	2	1.0	0.8
	fc37	4.97	2	1.0	0.8
	fc38	5.08	2	1.0	0.8
	fc131	7.34	3	0.8	0.8
	fc132	7.64	3	0.8	0.8
	fc133	7.43	3	0.8	0.8
	fc142	7.3	3	0.8	0.8
	fc143	7.39	3	0.8	0.8
	fc144	7.24	3	0.8	0.8
HR foam + polypro	fc75	2.65	14	1.0	0.75
	fc76	2.65	14	1.0	0.75
	fc77	2.52	14	1.0	0.75
	fc39	4.09	2	1.0	0.8
	fc134	5.94	3	0.8	0.8
	fc135	6.29	3	0.8	0.8
S. Polyurethane + cotton/linen	fc65	1.89	14	1.0	0.75
	fc67	1.91	14	1.0	0.75
	fc69	1.84	14	1.0	0.75
	fc29	3.78	2	1.0	0.8
	fc30	3.8	2	1.0	0.8
	fc32	3.79	2	1.0	0.8
	fc125	5.57	3	0.8	0.8
	fc126	5.41	3	0.8	0.8
	fc127	5.67	3	0.8	0.8
	fc136	5.57	3	0.8	0.8
	fc137	5.53	3	0.8	0.8
	fc138	5.54	3	0.8	0.8
Std Polyurethane + polypro	fc66	2	14	1.0	0.75
	fc68	1.95	14	1.0	0.75
	fc70	2.03	14	1.0	0.75
	fc28	4.09	2	1.0	0.8
	fc31	4.09	2	1.0	0.8
	fc33	4.09	2	1.0	0.8
	fc128	5.94	3	0.8	0.8
	fc129	5.92	3	0.8	0.8
	fc130	5.9	3	0.8	0.8
	fc139	6.29	3	0.8	0.8
	fc140	5.99	3	0.8	0.8
	fc141	5.85	3	0.8	0.8

Table 7.3 shows the auxiliary data, pertaining to the furniture specimens, required for *Model I*

Table 7.4 summarises the results based on the predictions from the University of Canterbury Cone tests and compares them with the full-scale tests as measured in the Furniture Calorimeter. The x_1 and x_2 values have been added for latter comparison.

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P)	Q''_{peak} (A) (kW)	Q_{total} (P)	Q_{total} (A) (MJ)	t_{peak} (P)	t_{peak} (A) (s)
HU-1	fc71	2.47	21	1236	680	267	43	34	122	100
	fc72	2.52	22	1241	682	292	44	37	122	80
	fc73	2.46	21	1235	680	258	43	35	122	85
HU-2	fc34	4.87	50	1337	787	111	84	13	150	108
	fc37	4.97	51	1344	792	120	86	12	151	98
	fc38	5.08	52	1351	797	132	88	23	151	28
HU-3R	fc131	7.34	66	1566	956	265	127	88	183	130
	fc132	7.64	70	1585	1005	311	132	98	184	83
	fc133	7.43	67	1572	971	296	128	78	183	91
HU-3C	fc142	7.3	66	1563	949	507	126	126	182	260
	fc143	7.39	67	1569	964	341	128	102	183	85
	fc144	7.24	65	1559	940	374	125	103	182	135

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P)	Q''_{peak} (A) (kW)	Q_{total} (P)	Q_{total} (A) (MJ)	t_{peak} (P)	t_{peak} (A) (s)
HP-1	fc75	2.65	37	1128	527	172	66	14	62	45
	fc76	2.65	37	1128	527	143	66	19	62	50
	fc77	2.52	34	1120	495	185	63	13	61	35
HP-2	fc39	4.09	63	1149	1149	110	102	10	68	40
	-									
	-									
HP-3R	fc134	5.94	80	1273	1273	185	148	12	78	40
	-									
	-									
HP-3C	fc135	6.29	86	1290	1290	205	157	17	79	30
	-									
	-									

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P)	Q''_{peak} (A) (kW)	Q_{total} (P)	Q_{total} (A) (MJ)	t_{peak} (P)	t_{peak} (A) (s)
SU-1	fc65	1.89	17	1222	664	272	34	46	78	105
	fc67	1.91	17	1224	665	365	34	47	78	80
	fc69	1.84	16	1215	662	314	33	44	77	80
SU-2	fc29	3.78	40	1324	752	625	68	95	93	122
	fc30	3.8	41	1326	753	378	68	72	93	110
	fc32	3.79	40	1325	752	589	68	94	93	118
SU-3R	fc125	5.57	52	1535	797	442	100	126	109	110
	fc126	5.41	50	1522	790	464	97	123	108	120
	fc127	5.67	53	1544	802	472	102	127	109	130
SU-3C	fc136	5.57	52	1535	797	693	100	121	109	137
	fc137	5.53	52	1532	795	662	99	119	109	115
	fc138	5.54	52	1533	796	631	99	118	109	105

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P)	Q''_{peak} (A) (kW)	Q_{total} (P)	Q_{total} (A) (MJ)	t_{peak} (P)	t_{peak} (A) (s)
SP-1	fc66	2	28	1109	397	396	47	44	62	60
	fc68	1.95	27	1105	384	410	46	44	62	45
	fc70	2.03	28	1112	404	459	48	45	62	60
SP-2	fc28	4.09	67	1183	854	848	96	89	72	75
	fc31	4.09	67	1183	854	719	96	84	72	102
	fc33	4.09	67	1183	854	348	96	34	72	70
SP-3R	fc128	5.94	86	1322	1322	630	139	103	83	90
	fc129	5.92	86	1321	1321	580	139	118	83	80
	fc130	5.9	85	1320	1320	770	138	136	83	135
SP-3C	fc139	6.29	92	1340	1340	1150	148	105	84	90
	fc140	5.99	87	1325	1325	1120	141	123	83	80
	fc141	5.85	84	1317	1317	1080	137	121	83	95

Table 7.4 shows the predicted vs the measured results based on the University of Canterbury's Cone tests.

Table 7.5 summarises the results based on the predictions from the CSIRO Cone tests and compares them with the full-scale tests as measured in the Furniture Calorimeter. The x_1 and x_2 values have been added for latter comparison in the **analysis of results** section.

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P) (kW)	Q''_{peak} (A) (kW)	Q_{total} (P) (MJ)	Q_{total} (A) (MJ)	t_{peak} (P) (s)	t_{peak} (A) (s)
HU-1	fc71	2.47	24	1205	342	267	51	34	141	100
	fc72	2.52	24	1209	350	292	52	37	142	80
	fc73	2.46	24	1204	340	258	51	35	141	85
HU-2	fc34	4.87	55	1298	798	111	101	13	175	108
	fc37	4.97	57	1304	819	120	103	12	176	98
	fc38	5.08	58	1311	841	132	106	23	177	28
HU-3R	fc131	7.34	74	1507	1507	265	153	88	214	130
	fc132	7.64	78	1525	1525	311	159	98	217	83
	fc133	7.43	75	1512	1512	296	155	78	215	91
HU-3C	fc142	7.3	74	1504	1504	507	152	126	214	260
	fc143	7.39	75	1510	1510	341	154	102	215	85
	fc144	7.24	73	1501	1501	374	151	103	214	135

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P) (kW)	Q''_{peak} (A) (kW)	Q_{total} (P) (MJ)	Q_{total} (A) (MJ)	t_{peak} (P) (s)	t_{peak} (A) (s)
HP-1	fc75	2.65	40	1142	570	172	69	14	74	45
	fc76	2.65	40	1142	570	143	69	19	74	50
	fc77	2.52	37	1133	536	185	66	13	73	35
HP-2	fc39	4.09	68	1164	1164	110	107	10	83	40
	-	-	-	-	-		-		-	
	-	-	-	-	-		-		-	
HP-3R	fc134	5.94	87	1295	1295	185	155	12	97	40
	-	-	-	-	-		-		-	
	-	-	-	-	-		-		-	
HP-3C	fc135	6.29	93	1312	1312	205	164	17	98	30
	-	-	-	-	-		-		-	
	-	-	-	-	-		-		-	

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P) (kW)	Q''_{peak} (A) (kW)	Q_{total} (P) (MJ)	Q_{total} (A) (MJ)	t_{peak} (P) (s)	t_{peak} (A) (s)
SU-1	fc65	1.89	17	1229	239	272	36	46	125	105
	fc67	1.91	17	1231	242	365	36	47	126	80
	fc69	1.84	16	1222	231	314	35	44	124	80
SU-2	fc29	3.78	39	1333	567	625	71	95	155	122
	fc30	3.8	40	1335	571	378	71	72	155	110
	fc32	3.79	40	1334	569	589	71	94	155	118
SU-3R	fc125	5.57	51	1548	1548	442	105	126	188	110
	fc126	5.41	49	1535	1535	464	102	123	187	120
	fc127	5.67	52	1557	1557	472	107	127	189	130
SU-3C	fc136	5.57	51	1548	1548	693	105	121	188	137
	fc137	5.53	51	1545	1545	662	104	119	188	115
	fc138	5.54	51	1546	1546	631	104	118	188	105

	test	m_{soft} (kg)	x_1	x_2	Q''_{peak} (P) (kW)	Q''_{peak} (A) (kW)	Q_{total} (P) (MJ)	Q_{total} (A) (MJ)	t_{peak} (P) (s)	t_{peak} (A) (s)
SP-1	fc66	2	26.9	1184	388	396	58	44	65	60
	fc68	1.95	26.1	1178	376	410	56	44	64	45
	fc70	2.03	27.4	1187	395	459	58	45	65	60
SP-2	fc28	4.09	65.9	1281	949	848	118	89	76	75
	fc31	4.09	65.9	1281	949	719	118	84	76	102
	fc33	4.09	65.9	1281	949	348	118	34	76	70
SP-3R	fc128	5.94	84	1466	1466	630	171	103	88	90
	fc129	5.92	83.7	1464	1464	580	170	118	87	80
	fc130	5.9	83.3	1463	1463	770	170	136	87	135
SP-3C	fc139	6.29	90.3	1489	1489	1150	181	105	89	90
	fc140	5.99	84.9	1469	1469	1120	172	123	88	80
	fc141	5.85	82.4	1459	1459	1080	168	121	87	95

Table 7.5 shows the predicted vs the measured results based on CSIRO's Cone tests.

Table 7.6 shows the comparison data between the cone tests conducted at 15, 25 and 35kW heat fluxes at CSIRO. This was done to see the relative impacts and fabric effects that become dominant at different heat fluxes.

	Property	Specimen A	Specimen B	Specimen C	Mean	σ	Variation
15kW heat flux	mass (g)	29	28.7	28.7	28.8	0.2	0.6%
	t_{ig} (s)	27	26	29	27	1.5	5.6%
	t_{peak} (s)	150	180	155	162	16.1	10%
	q''_{peak} (kW/m2)	500	513	507	507	6.5	1.3%
	q_{total} (MJ/m2)	98.7	98.8	100.8	99.4	1.2	1.2%
	$\Delta h_{c,eff}$ (MJ/kg)	34.0	34.4	35.1	34.5	0.6	1.6%
25kW heat flux	mass (g)	28.5	28.9	28.9	28.8	0.2	0.8%
	t_{ig} (s)	14	12	15	14	1.5	11%
	t_{peak} (s)	125	110	135	123	12.6	10%
	q''_{peak} (kW/m2)	541	540	534	538	3.8	0.7%
	q_{total} (MJ/m2)	102.6	106.7	110	106.4	3.7	3.5%
	$\Delta h_{c,eff}$ (MJ/kg)	36.0	36.9	38.1	37.0	1.0	2.8%
35kW heat flux	mass (g)	28.5	28.9	28.6	28.7	0.2	0.7%
	t_{ig} (s)	8	28	7	14	11.8	83%
	t_{peak} (s)	85	105	85	92	11.5	13%
	q''_{peak} (kW/m2)	547	548	551	549	2.1	0.4%
	q_{total} (MJ/m2)	97.6	98.8	99.8	98.7	1.1	1.1%
	$\Delta h_{c,eff}$ (MJ/kg)	34.2	34.2	34.9	34.4	0.4	1.1%

Table 7.6 shows the cone test fire results for the *High Resilience Polyurethane* foam + polypropylene fabric under the influence of three different heat fluxes.

7.2 Furniture Calorimeter data

This is summarised above in **Tables 7.4 & 7.5**. **Table 7.7** overleaf presents the standard deviation and variation between each test within each triplicate series for the total heat released. This is thought the best initial indicator for checking the overall repeatabilty of a fire experiment.

As a follow up to this report a study into how the propagation of uncertainty travels through the correlation equations should be conducted. This will determine the confidence levels that can be used stated when using these results.

ITEM CODE	FURNITURE SPECIMEN (TOTAL HEAT RELEASED) (MJ)			MEAN	STD DEV	VARIATION (%)
	1	2	3			
1SU	46	47	44	46	2	3%
1SP	44	44	45	44	1	1%
1HU	34	37	35	35	2	4%
1HP	14	19	13	15	3	21%
2SU	95	72	94	87	13	15%
2SP	89	84	34	69	30	44%
2HU	12	13	23	16	6	38%
2HP	10	-	-	10	-	-
3SU-R	126	123	127	125	2	2%
3SP-R	103	118	136	119	17	14%
3HU-R	88	98	78	88	10	11%
3HP-R	12	-	-	12	-	-
3SU-C	121	119	118	119	2	1%
3SP-C	105	123	121	116	10	8%
3HU-C	126	102	103	110	14	12%
3HP-C	17	-	-	17	-	-

Table 7.7 shows the variation between tests for the Furniture Calorimeter. The item code summarises the construction details of the test triplicate, with the symbols meaning the following in this order; 1,2,3 = one, two or 3 seater ; S, H= ***Standard*** **or** ***High Resilience Polyurethane*** **foam; U, P = cotton/linen or polypropylene fabric; and R, C = right hand or centre ignition crib location.**

8 ANALYSIS OF RESULTS

8.1 Cone Calorimeter

There were three separate Cone Calorimeter test series conducted at both CSIRO and the University of Canterbury's Fire laboratory. The exact nature of construction of the cone samples in the first series of tests, conducted over six years ago at CSIRO was not clearly documented. For this reason and to see if there were any aging effects in the original foam and fabric materials, another series of tests was conducted at the University of Canterbury on samples constructed from the original materials. These were constructed according to the CBUF protocol guidelines as detailed in appendix A6 of their report. As a baseline a further series of tests were conducted at heat flux irradiances of 15, 25 and 35 kWm^{-2} upon one of the foam + fabric combinations, (High Resilience + polypropylene), these samples were constructed and tested at CSIRO, just prior to the tests at the University of Canterbury. They were constructed in the same manner as the original samples, but tested with an edge frame.

8.1.1 University of Canterbury Cone Calorimeter analysis of results

These results illustrated quite distinctive behaviour and will be discussed for each fabric and foam combination. Also tested were the foam samples without any fabric covering. This enabled comparisons to be made between the heat release rates and total heat release, contributed by the fabric.

8.1.1.1 Standard Polyurethane foam only

A total of 4 tests were conducted on this series, the results of which are summarised in **Table 7.2** of the results section. The three closest fitting HRR curves (within 5% @ q''_{180}) are graphically displayed overleaf in **fig 8.1**. They all ignited within the first 6 seconds and burnt with a strong single peak, of about 420kWm^{-2}. Their burning duration was the shortest of all the test series, with flaming generally lasting for less than 150 seconds.

8.1.1.2 Standard Polyurethane foam + polypropylene fabric

A total of 3 tests were conducted for this series, the results of which are summarised in **Table 7.2**.

These are graphically displayed overleaf in **fig 8.2**. They all ignited within the first 10 seconds and burnt with a series of strong peaks, of around 450 - 500kWm^{-2}. Their burning duration was the second shortest of all the test series, with flaming generally lasting for about 220 seconds. The polypropylene fabric did delay the ignition time, even though it rapidly split and melted, within 2 - 4 seconds of being subjected to the cone s' heat flux. It also contributed to the total heat release, which was greater by a factor of two, and to the peak HRR, which was approximately a quarter higher. Although HRR was jagged during peak burning, subjective judgement determined the 1st trough and 2nd peak values that are necessary for the predictive modelling as laid down in the CBUF report. The standard deviations of these values are shown in **Table 7.2.** Due to the fire intensity of this foam + fabric combination the aluminium foil cup, experienced quite noticeable oxidation, with the bottom containing burnt through holes by the tests' end.

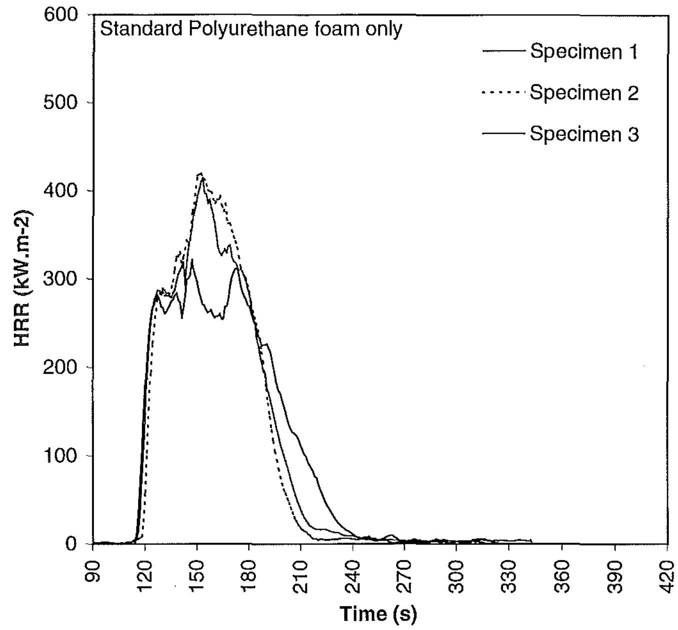

Figure 8.1 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for the *Polyurethane* foam only

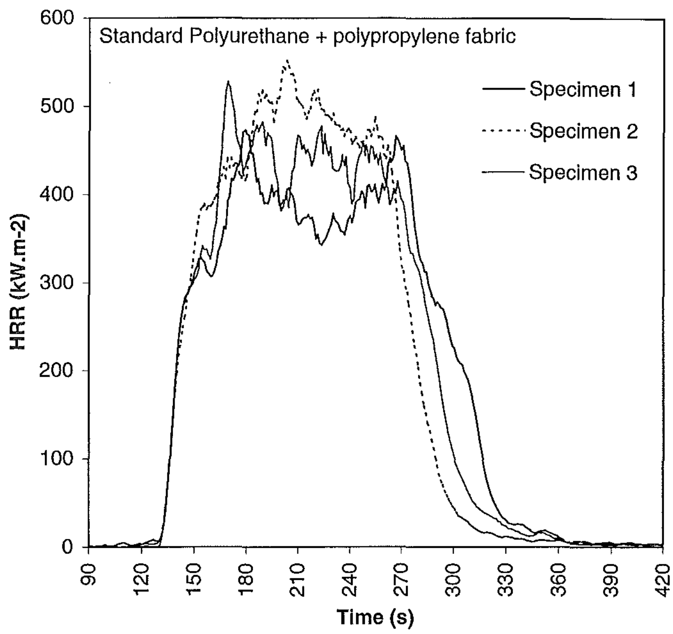

Figure 8.2 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for *Standard Polyurethane* foam + polypropylene fabric.

8.1.1.3 Standard Polyurethane foam + cotton/linen fabric

A total of 3 tests were conducted for this series, the results of which are summarised in **Table 7.2**. These are graphically displayed below in **fig 8.3**. They all ignited within the first 12 seconds and burnt with a strong 1st peak, of about 350kWm^{-2}. Their burning duration was the second longest of all the test series, with flaming generally lasting for at least 300 seconds. As can be seen fabric effects did delay the ignition time and drew out the combustion reaction. The cotton fabric charred, but remained intact for almost the entire test, only completely disintegrating about 60 – 90 seconds prior to its' end. From **Table 7.2** it can be seen that the fabric also added to the total heat released. The 1st trough and 2nd peak values that are necessary for the predictive modelling as laid down in the CBUF report, were very clearly discernible and have considerably less variation than the polypropylene fabric. These can be viewed from the standard deviations values as shown in **Table 7.2.**

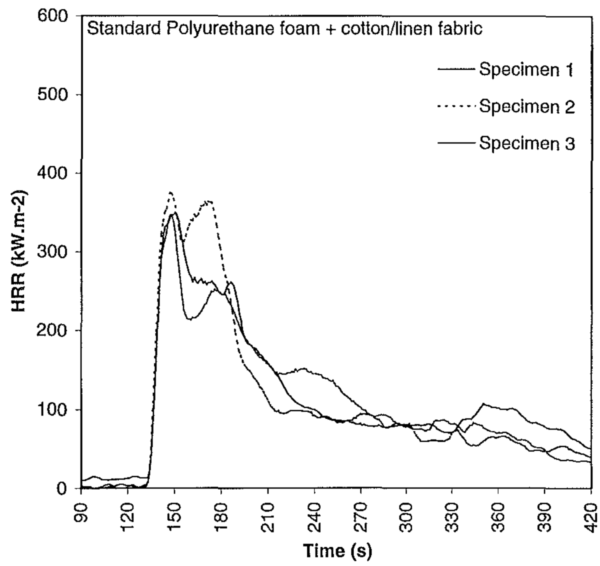

Figure 8.3 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for the *Standard Polyurethane* foam + cotton/linen fabric tests.

8.1.1.4 High Resilience foam only

A total of 7 tests were conducted for this series, the results of which are summarised in **Table 7.2**. The three closest fitting HRR curves (within 5% @ q''_{180}) are graphically displayed overleaf in **fig 8.4**. They all ignited within 5 seconds, except for one test, which took 46 seconds. They all exhibited almost symmetrical HRR curves, with a strong single peak occurring in the middle of the test, of about 330kWm^{-2}. Their burning duration was also quite short, with flaming generally (two had flaming periods of 210 seconds) lasting for approximately 180 seconds. The unpredictable behaviour of this foam is not easily explained. However it was observed that during the tests this foam exhibited a peculiar froth that lay on top of the melted foam between the approximate times of 30 - 90 seconds after ignition.

Although it did not appear to inhibit burning, it is thought that this froth consisted of chemical additives designed to lessen the *hardness* of the foam (this is discussed earlier in the report). It is thought that these chemical additives caused these greater observed variations in ignition and burning duration times.

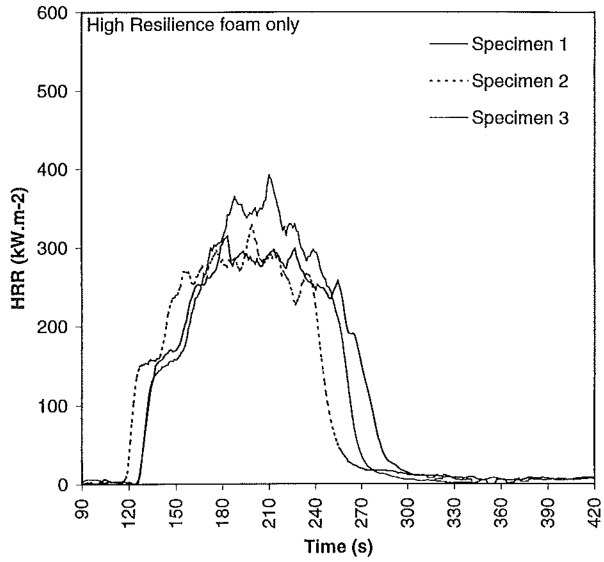

Figure 8.4 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for the *High Resilience Polyurethane* foam only.

8.1.1.5 High Resilience foam + polypropylene fabric

A total of 4 tests were conducted for this series, the results of which are summarised in **Table 7.1**.

These are graphically displayed below in **fig 8.5**.

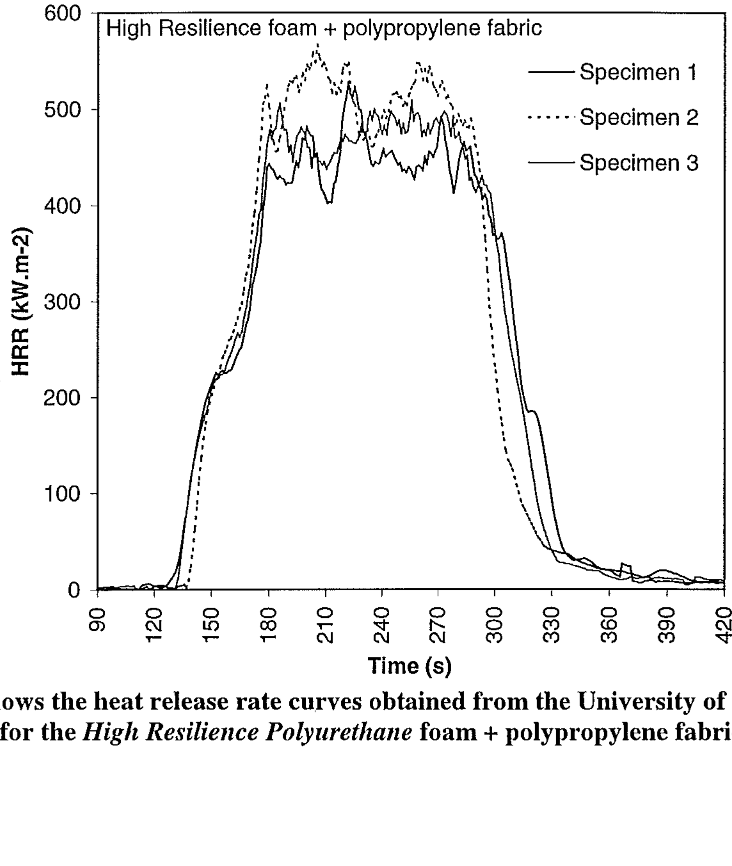

Figure 8.5 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for the *High Resilience Polyurethane* foam + polypropylene fabric tests.

They all had varying ignition times, ranging generally from between 9 - 16 seconds with one test displaying 36 seconds. Once again the tests yielded HRR curves that were generally symmetrical with two dominant peaks (and a trough in between them) of between 500 - 550 kWm^{-2}. These values are very similar to those obtained for the Standard Polyurethane foam + polypropylene fabric. Their burning duration was quite varied, with flaming lasting for about 230 seconds for the first two and about 260 for the last two tests. The polypropylene fabric did delay the ignition time, even though it rapidly split and melted, within 2 - 4 seconds of being subjected to the cone s' heat flux. But its' most noticeable contribution was to the to the total heat release and peak HRR, both being almost twice the value. HRR was quite jagged during peak burning, and subjective judgement determined the 1st trough and 2nd peak values that are necessary for the predictive modelling of the full-scale furniture as laid down in the CBUF report. The standard deviations of these values are shown in **Table 7.2.**

8.1.1.6 High Resilience foam + cotton/linen fabric

A total of 5 tests were conducted for this series, the results of which are summarised in **Table 7.2.**

These are graphically displayed below in **fig 8.6.**

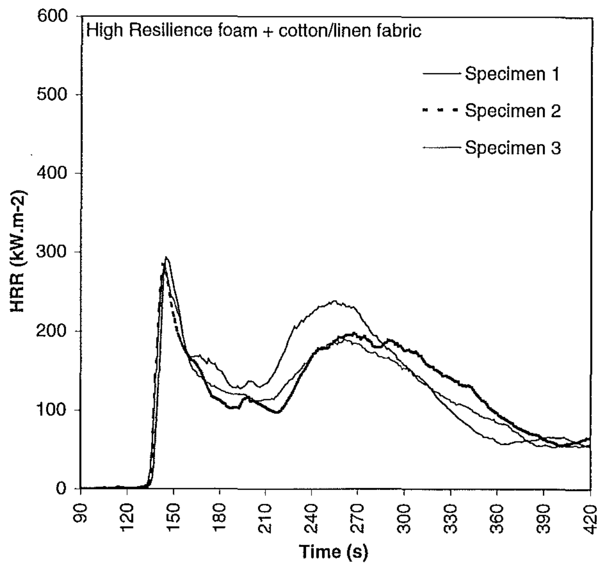

Figure 8.6 shows the heat release rate curves obtained from the University of Canterbury's Cone Calorimeter for the *High Resilience Polyurethane* foam + cotton/linen fabric tests.

They all ignited within 12 - 18 seconds and burnt with a strong 1st peak, of about 300kWm^{-2}. Their burning duration was the longest of all the test series, with flaming generally lasting for at least 420 seconds (one test lasted for 522 seconds). As can be seen fabric effects did delay the ignition time and drew out the combustion reaction. The cotton fabric charred, but remained intact for the entire test, only being compromised in the corners of the test samples, and only towards the very end. From **Table 7.2** it can be seen that the fabric, contributed very little to the overall heat release. This is in stark contrast to the same tests but with the Standard Polyurethane foam, where almost a quarter more heat is released. These tests displayed very clear 1st trough and 2nd peak values, but were quite varied in their times and HRR values. These can be viewed from the standard deviations values as shown in **Table 7.2.**

8.1.1.7 Foam and fabric interaction effects

In addition to the original series of tests conducted at CSIRO on the foam + fabric combinations, a further two sets of tests were conducted on just the foam blocks. These results are shown in **figures 8.7 – 8.10** to highlight the impact of the fabric in the combustion reaction. Most noticeable is the contribution that the polypropylene fabric gives to both the total heat released and HRR. For both foams as can be seen in **fig 8.7 & 8.8** the presence of the polypropylene fabric increases the peak HRR by between 40 –50%. This level is sustained, well after the sample with just the foam has died out. As can be seen from **Table 7.2** the contribution to the total heat released has been more than doubled. (27 MJm^{-2} vs 64.4 MJm^{-2} for the Standard Polyurethane foam without and with polypropylene fabric, respectively and 36 MJm^{-2} vs 74.3 MJm^{-2} for the High Resilience foam without and with the polypropylene fabric, respectively). Furthermore the polypropylene fabric does not significantly delay the ignition time of the sample, lessening the hazard. Observations of the fabric show that it shrinks, splits and melts in that order, prior to ignition and within 3 – 4 seconds from being placed under the radiant cone heater.

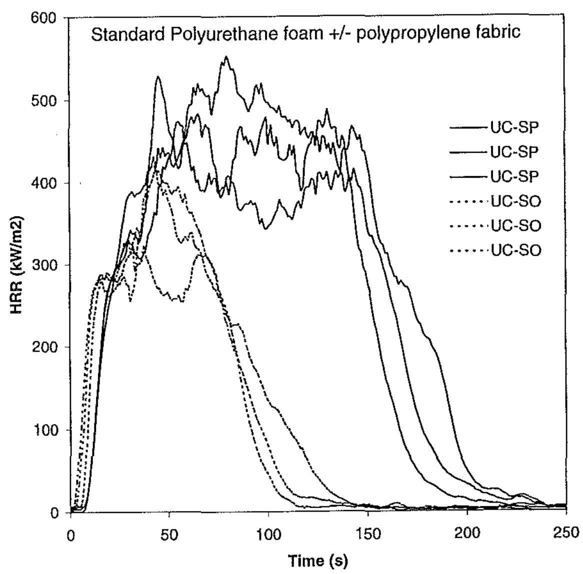

Figure 8.7 illustrates the difference in the HRR curve for the *Standard Polyurethane* foam with and without the polypropylene fabric cover. The dotted lines show the *Standard Polyurethane* foam only, whilst the solid lines show the *Standard Polyurethane* foam + polypropylene fabric. Tests are shown conducted in triplicate.

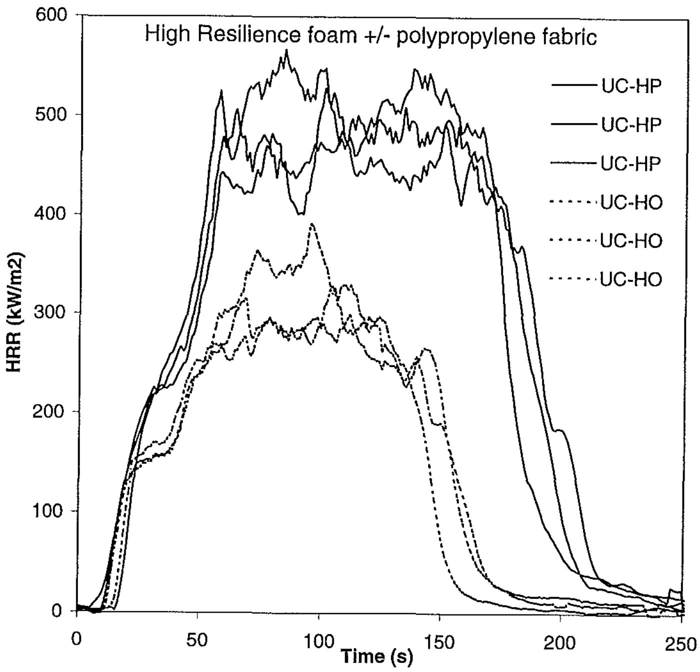

Figure 8.8 illustrates the difference in the HRR curve for the *High Resilience Polyurethane* foam with and without the polypropylene fabric cover. The dotted lines show the *High Resilience Polyurethane* foam only, whilst the solid lines show the *High Resilience Polyurethane* foam + polypropylene fabric. Tests are shown conducted in triplicate.

The results from the cotton/linen fabric tests shown in **figures 8.9 & 8.10** overleaf, illustrate that not only does the fabric reduce the peak heat release rate, but also tends to lower the overall HRR. The fabric achieves this effect by remaining as a cover over the foam for a much longer time, restricting the free combustion of the foam and thus prolonging the burning reaction. The earlier dominant peak exhibited in the samples with the cotton/linen fabric is of short duration, peculiar only to the Cone Calorimeter, and doesn't truly represent what occurs in the full scale tests. Observations of the fabric show that it chars but retains its' general integrity for the majority of the test. As can be seen from **Table 7.2** the contribution to the total heat released is not significant, being only about an 8 – 25% increase for the High Resilience and Standard Polyurethane foams, respectively. The following values have been extracted from **Table 7.2**, 27 MJm^{-2} vs 35.9 MJm^{-2} for the Standard Polyurethane foam without and with cotton/linen fabric, respectively and 36 MJm^{-2} vs 39 MJm^{-2} for the High Resilience foam without and with the polypropylene fabric, respectively. Although the cotton/linen fabric does not significantly delay the ignition time of the sample, this is not an accurate reflection of what one would expect in the full-scale tests, being only peculiar to the Cone Calorimeter. It is interesting to note that there are quite distinct and separate mechanisms that are occurring in the two different foams when protected with the cotton/linen fabric. From observation, the *Standard Polyurethane* foam forms a pool fire much sooner than the *High Resilience Polyurethane* foam and thus becomes volatised earlier.

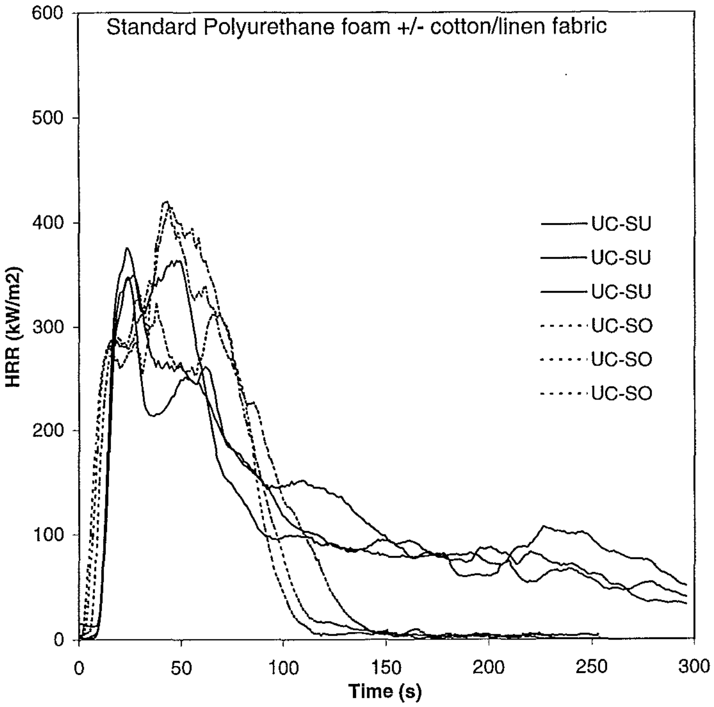

Figure 8.9 illustrates the difference in the HRR curve for the *Standard Polyurethane* foam with and without the cotton/linen fabric cover. The dotted lines show the *Standard Polyurethane* foam only, whilst the solid lines show the *Standard Polyurethane* foam + polypropylene fabric. Tests are shown conducted in triplicate.

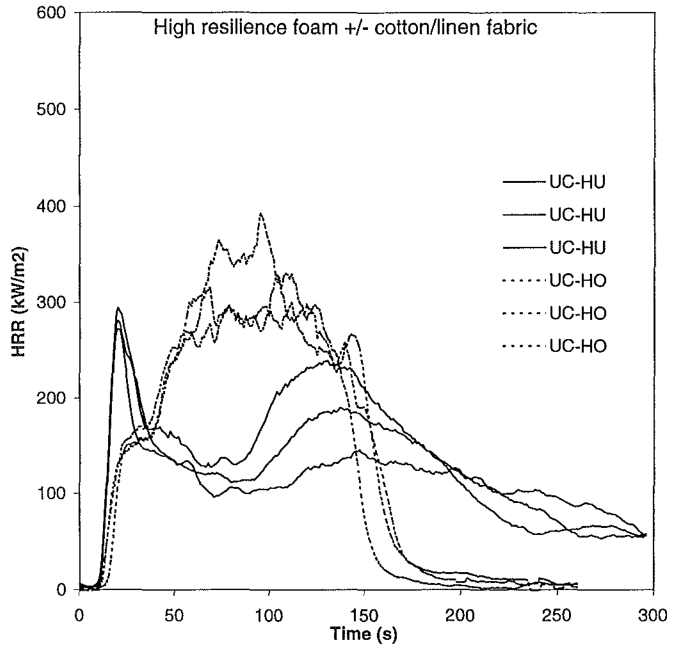

Figure 8.10 illustrates the difference in the HRR curve for the *High Resilience Polyurethane* foam with and without the cotton/linen fabric cover. The dotted lines show the *High Resilience Polyurethane* foam only, whilst the solid lines show the *High Resilience Polyurethane* foam + cotton/linen fabric. Tests are shown conducted in triplicate.

8.1.1.8 High Resilience foam variations

This foam produced the widest variation in observed results and for this reason an extended series of tests were performed on the foam alone, to see what the distribution of its' total heat release and peak heat release values were. This variation is not easily explained, as the constitution of the foam is not known, however, from observations, during testing a protective frothing layer tended to form over the melted foam. This composition of this froth is also unknown. The graphical results of the HRR curves are displayed below in **fig 8.11. Table 8.1** overleaf illustrates the variation between the tests for some of the more important parameters. The results from these tests are important as they illustrate in the small-scale the unpredictability associated with this foam. One sample took 46 seconds to ignite! This is especially important as in the Cone Calorimeter the samples are subjected to a very high heat flux, which should overcome most differences in ignition characteristics.

Parameter	Specimens						Mean	σ	Variation
	1	2	3	4	5	6			
m (g)	16.79	16.79	16.79	16.44	16.43	16.50	**16.6**	**0.2**	**1**
t_{ig} (s)	3	5	3	4	5	46	**11.0**	**17**	**156**
Q_{total} (MJm^{-2})	35.7	35.8	36.1	36.6	36.1	33.5	**35.6**	**1.1**	**3**
q''_{180} (kW)	196	192	211	197	196	188	**197**	**7.8**	**4**
q''_{peak} (kW)	315	328	392	384	340	314	**346**	**34**	**10**
t_{peak} (s)	60	94	87	88	133	113	**96**	**25**	**26**
$\Delta h_{c,eff}$ ($MJkg^{-1}$)	20.1	22.3	20.5	21.0	20.7	19.6	**20.7**	**0.9**	**4**

Table 8.1 shows the variation between the cone tests conducted on the *High Resilience Polyurethane* foam samples

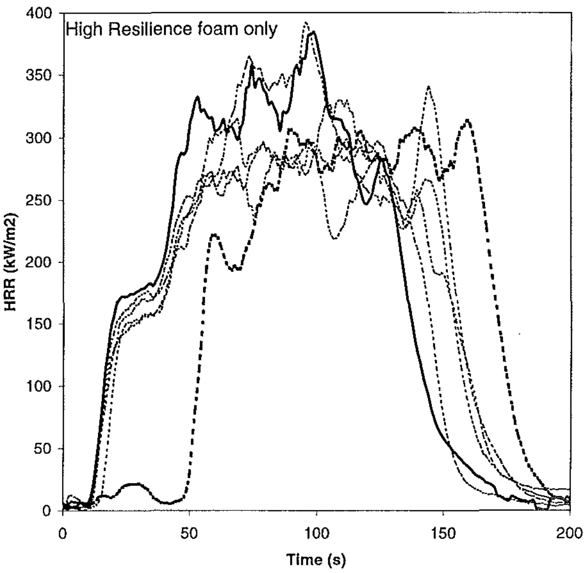

Figure 8.11 illustrates the difference in the HRR curves for just the *High Resilience Polyurethane* A total of 7 tests were conducted, 6 are shown above. The bold solid line illustrates the most dominant HRR curve obtained, whilst the bold dotted line illustrates the smallest HRR obtained, which came from the test that took 46 seconds to ignite.

8.1.2 CSIRO Cone Calorimeter analysis of results

Two sets of tests were conducted at CSIRO. The original series is described first being tested at heat flux irradiances of 25 & 35 kWm^{-2}. The cone samples of both sets were each constructed in the same way, (100 x 100 x 50 mm foam block covered with a $200mm^2$ of fabric, pulled closely around the block, with the edges folded on the diagonal and stapled to the fabric on the sides). The second set of tests were conducted on only one fabric + foam combination, but at heat flux irradiances of 15, 25 & 35 kWm^{-2}. These results illustrated quite distinctive behaviour and will be discussed for each fabric and foam combination.

The results from both sets of tests are summarised in brief in **Table 7.1 and 7.6** of the results section for the original and three different heat flux series respectively.

They have used an averaging process, (measurements were taken at 1 second intervals, and averaged over 5 seconds) in the recording of their raw data. This makes them appear much smoother than those obtained from the tests conducted at the University of Canterbury, (which uses 10 samples of 0.1-second intervals to obtain an average reading every 1-second).

8.1.3 CSIRO Cone tests for the original series

These tests were conducted at two different heat fluxes (25 and 35kWm^{-2}) and the comparisons of them are displayed in **fig 8.12 – 8.15**. Each test triplicate displays quite distinctive behaviour due to the particular foam + fabric construction. The bulk of these observations have already been discussed, so what follows below is peculiar only to these tests. For the purposes of easy comparison the test triplicates at both irradiances, for the same foam + fabric combination are graphed together. The 25 kWm^{-2} tests are shown as the dotted line.

8.1.3.1 Standard Polyurethane foam + polypropylene fabric

The HRR of this test triplicate is displayed graphically in **fig 8.12** below. As is illustrated a dominant single peak is reached of about 450 – 500 kWm^{-2}. Burning behaviour is generally very even, almost symmetrically so, with burn duration being 200 seconds.

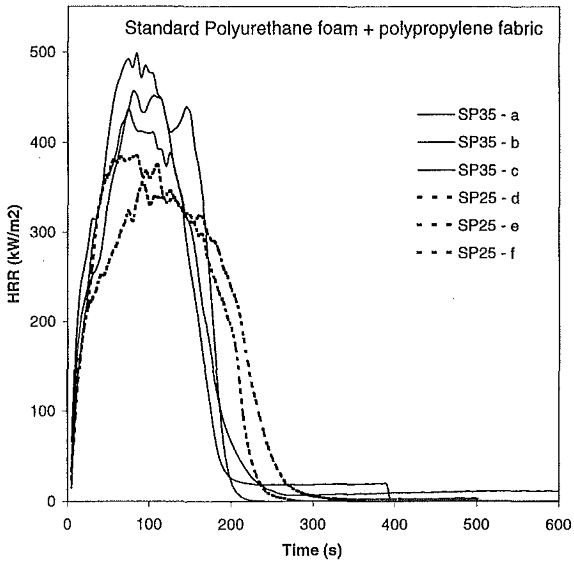

Figure 8.12 shows the CSIRO conducted HRR curve for *Standard Polyurethane* foam + polypropylene fabric. Two sets of test triplicates are shown, one at 35 kWm^{-2} the other at 25 kWm^{-2} heat flux irradiance

8.1.3.2 Standard Polyurethane foam + cotton/linen fabric

The HRR of this test triplicate is displayed graphically in **fig 8.13** below. For the 35 kWm^{-2} tests, a very sharp dominant single peak is reached at the beginning of the test of about 250 – 300 kWm^{-2}, thought to be directly derived from the sudden piloted ignition of a build up of pyrolysed foam, built up just prior to ignition. Burning behaviour after this quickly settles down to a more or less even level of approximately 120 kWm^{-2} and is generally very even, although a quite distinctive trough and peak HRR at 120 seconds after ignition is visible. This second peak is thought to be due to the final degradation of the cotton/linen fabric, which then allows freer burning to occur. Burn duration is of the order of 350 seconds. The 25 kWm^{-2} test triplicates display very similar behaviour but are reduced in peak HRR and stretched in burning duration. They reach their second peak almost 3 minutes later than the 35 kWm^{-2} tests. It is interesting to note that at this lower irradiance the burning behaviour is less well defined, with a series secondary and tertiary troughs and peaks. This behaviour is not easily explained.

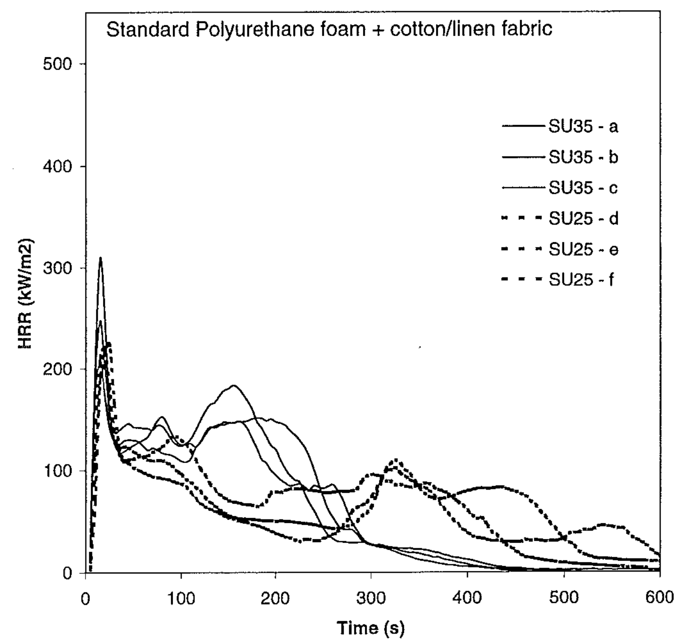

Figure 8.13 shows the CSIRO conducted HRR curve for *Standard Polyurethane* foam + cotton/linen fabric. Two sets of test triplicates are shown, one at 35 kWm^{-2} the other at 25 kWm^{-2} heat flux irradiance.

8.1.3.3 High resilience foam + polypropylene fabric

The HRR of this test triplicate is displayed graphically in **fig 8.14** overleaf. For the 35 kWm^{-2} tests a dominant single peak is reached of about 450 kWm^{-2} at approximately 100 seconds after ignition. For the 25 kWm^{-2} tests there is the presence of a HRR trough and second peak, the latter thought to be due to the diminishing volume of melted foam reaching a point where the dominant behaviour is vaporisation, rather than bulk heating, (convective processes) of the remaining foam. Burning behaviour is generally very repeatable within each of and between the test triplicates, with burn duration being 250 seconds. It appears that at the 35 kWm^{-2}

irradiance the *High Resilience Polyurethane* foam + polypropylene fabric samples result in a more efficient combustion reaction as more total heat is released. This is due to the higher temperatures achieved, volatising more combustible matter.

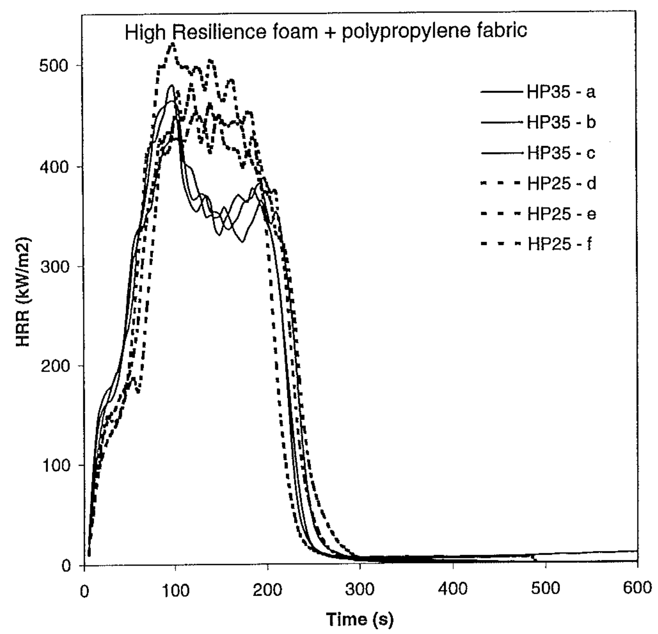

Figure 8.14 shows the CSIRO conducted HRR curve for *High Resilience Polyurethane* foam + polypropylene fabric. Two sets of test triplicates are shown, one at 35 kWm^{-2} the other at 25 kWm^{-2} (dotted line) heat flux .

8.1.3.4 High Resilience foam + cotton/linen fabric

The HRR of this test triplicate is displayed graphically in **fig 8.15** below.

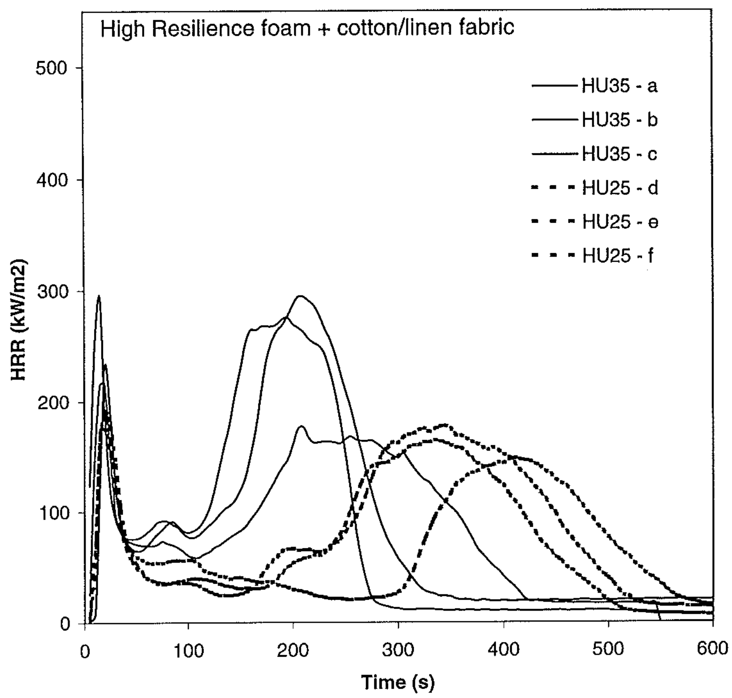

Figure 8.15 shows the CSIRO conducted HRR curve for *High Resilience Polyurethane* foam + cotton/linen fabric. Two sets of test triplicates are shown, one at 35 kWm^{-2} the other at 25 kWm^{-2} (dotted line) heat flux

For the 35 kWm^{-2} a very sharp although not dominant single peak of between 230 – 290 kWm^{-2} is reached within 5 seconds of ignition, similar in characteristics to the other cotton/linen fabric with the *Standard Polyurethane* foam. The duration of this peak is for only about 10 seconds with the HRR quickly dropping down to a level of 75 kWm^{-2}, before rising to a second dominant peak. This strong sharp peak is also thought to be due to the sudden ignition of built up pyrolysis products. The cotton/linen fabric delays this ignition time through, it is thought, two separate processes. First it inhibits the heat from the radiant cone heater from obtaining a direct attack on the foam. And secondly it prevents completely free combustion, with the air having to either flow in through the fabric, or wait until the vaporised foam flows out before it can mix with it and combust. Based on observations of flaming under the fabric for the same samples in the University of Canterbury's tests, it is thought that both airflow scenarios occur. After approximately 100 seconds one of the tests within the triplicate, displays quite reduced but prolonged burning behaviour with a burn duration being 150 seconds longer than its' comparative samples, which burn out at around 300 seconds. A very distinctive and extended HRR trough and second peak are displayed, again thought to be due to the fabric inhibiting the combustion reaction, then once sufficiently deteriorated, allowing a free burning environment to occur. It is important to note that this second peak is the dominant peak, and should be the peak against which hazard calculations are based upon, providing the fabric covering displays the same characteristics in the full-sized furniture specimen. The 25 kWm^{-2} illustrate very similar behaviour, albeit stretched in time scale and reduced in HRR.

8.1.4 CSIRO Cone results at varying heat flux irradiances

For comparison further tests were conducted (December 1998) on the High Resilience foam + polypropylene fabric combination at three different heat flux irradiances (15, 25 & 35kWm^{-2}). It is unfortunate that an edge frame was used for these tests, otherwise direct comparisons could have been made for this series across the two different labs and three different time periods when the tests were conducted. The results are illustrated overleaf in **fig 8.16 – 8.19**.

8.1.4.1 Comparison of *High Resilience Polyurethane* foam + polypropylene fabric at different heat fluxes

At the 15 kWm^{-2} heat flux irradiance as shown in **fig 8.16** overleaf the *High Resilience Polyurethane* foam + polypropylene fabric exhibits a short distinctive trough after approximately 90 seconds of burning. The reason for this sharp trough is unknown. After this a very strong and broad burning period develops, reaching a peak around 500 kWm^{-2}.

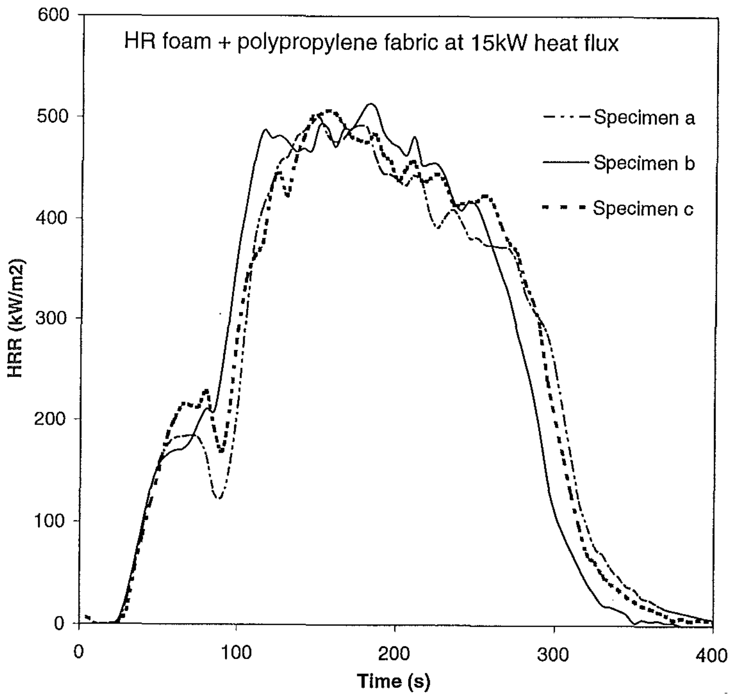

Figure 8.16 shows the Cone Calorimeter tests triplicate results for the *High Resilience Polyurethane* foam + polypropylene fabric at 15 kWm^{-2}

At the 25 kWm^{-2} heat flux irradiance as shown in **fig 8.17** below, this first trough is reduced but a minor second trough appears. A peak heat release rate of 530 kWm^{-2} is reached and maintained with only a gradual steady loss until burning relatively abruptly stops.

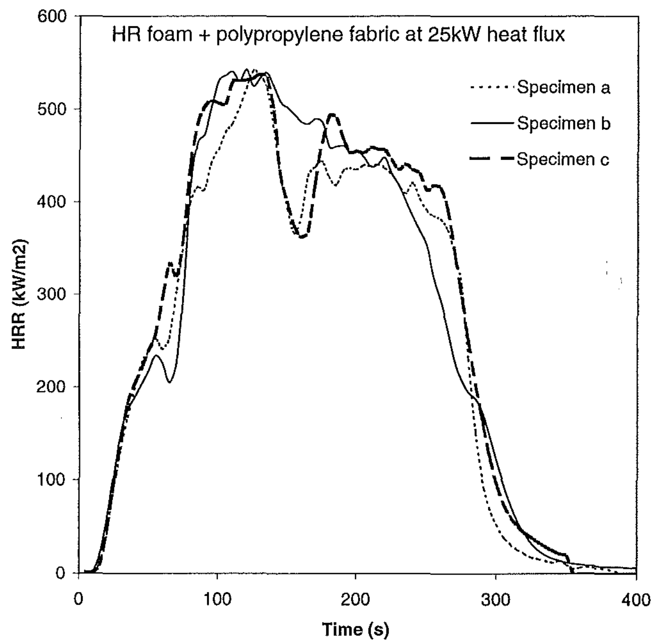

Figure 8.17 shows the Cone Calorimeter tests triplicate results for the *High Resilience Polyurethane* foam + polypropylene fabric at 25 kWm^{-2}

At the 35 kWm^{-2} heat flux irradiance as shown in **fig 8.18** overleaf, this first trough is reduced even further. However the presence of a dominant prolonged second trough appears. A peak but shorter, heat release rate of 540 kWm^{-2} is reached. Once again these test triplicate series is characterised with quite an abrupt end to the burning stage. A second but significant peak is reached just prior to specimen burnout.

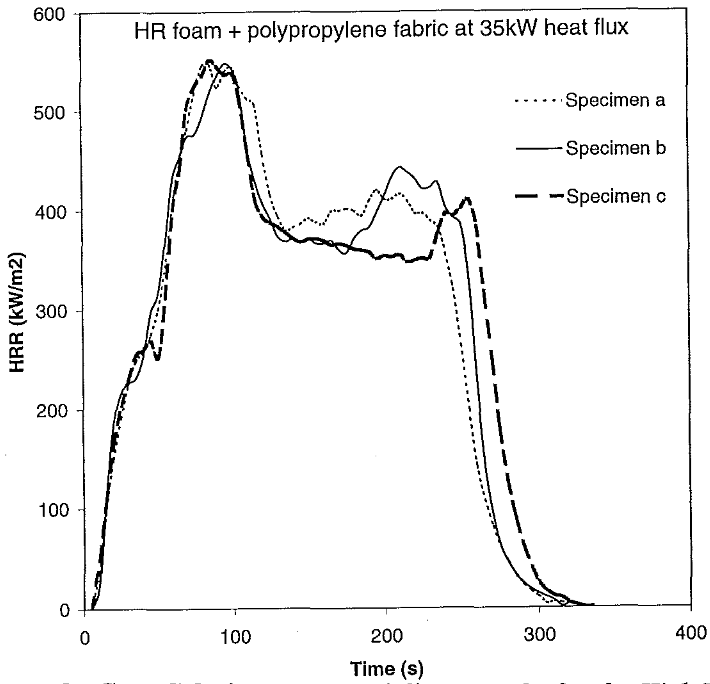

Figure 8.18 shows the Cone Calorimeter tests triplicate results for the *High Resilience Polyurethane* foam + polypropylene fabric at 35 kWm^{-2}

Exemplary HRR curves of the *High Resilience Polyurethane* foam + polypropylene fabric at the three different heat flux irradiances are shown below in **fig 8.19** to allow direct comparisons to be made. Perhaps the most visible and important result is that at higher irradiances a higher peak HRR occurs in a shorter time after ignition.

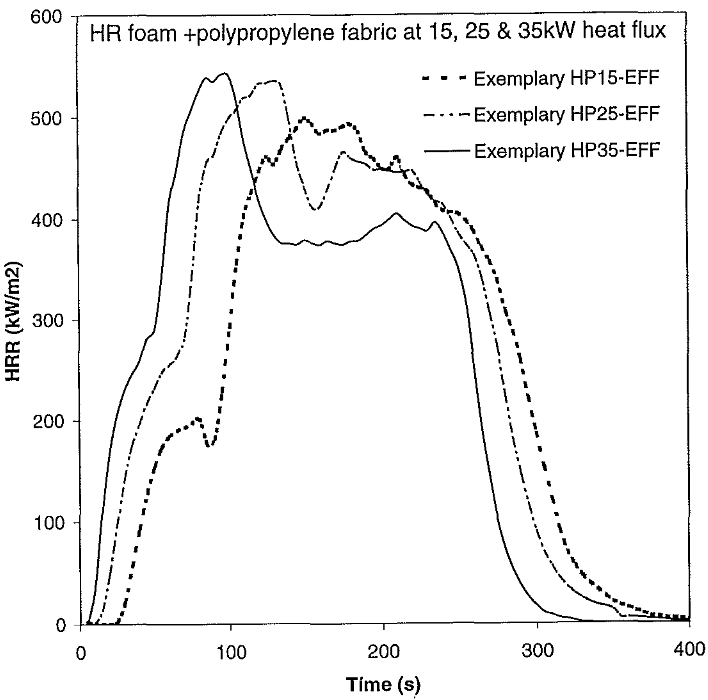

Figure 8.19 shows exemplary HRR curves for the Cone Calorimeter results of the *High Resilience Polyurethane* foam + polypropylene fabric at 15, 25 & 35 kWm^{-2} heat flux irradiances.

8.1.4.2 Comparison between edge frame and no edge frame

Although it is not appropriate to read too much into the differences observed between the corresponding tests with and without the edge frame, it is interesting to note that its use does exhibit a very dominant effect. It is important to note that the weights of the samples were very similar (within 3 – 4 grams). Yet the total heat released for the edge frame samples was almost twice as much, over both heat fluxes. The protocol under which these tests were conducted at CSIRO (AS/NZS 3837:1998 – section III) lays down a scaling factor for weighting the heat release rate, based on the exposed surface area. For the edge frame this is an initially exposed surface of $0.0088m^2$, without the edge frame it is $0.01m^2$. The comparison graphs are shown below in fig **8.20 – 8.21**. For **fig 8.20** the scaling factor of $0.0088m^2$ has been used, for **fig 8.21** the scaling factor of $0.01m^2$ has been used.

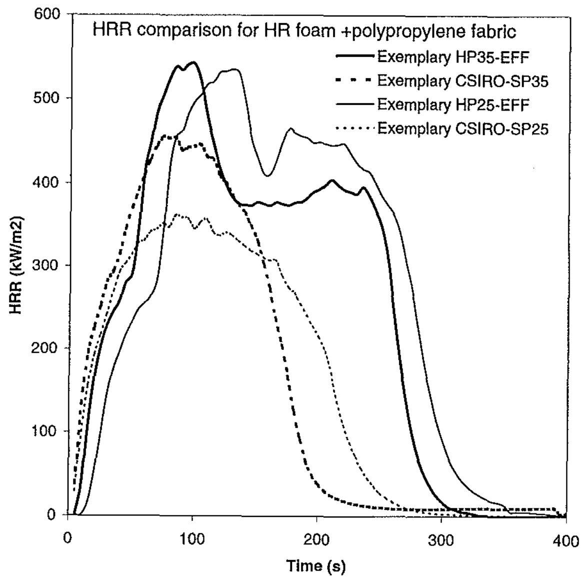

Figure 8.20 shows the exemplary HRR curves for the *High Resilience Polyurethane* foam + polypropylene fabric with the official edge factor correction applied, compared with the corresponding earlier tests conducted without any edge frame. EFF stands for edge frame factor (0.008).

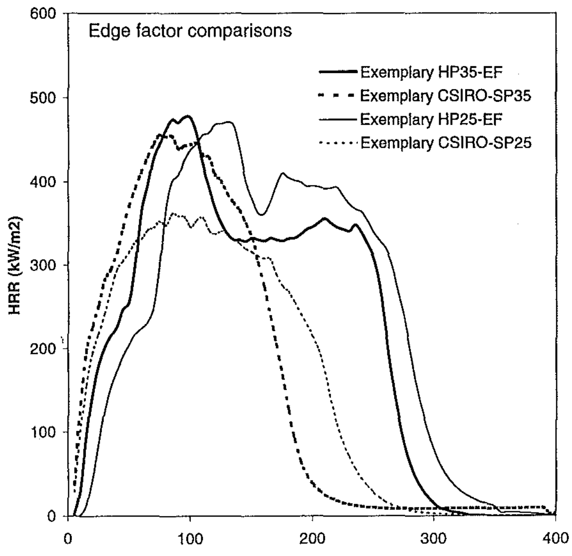

Figure 8.21 shows the exemplary HRR curves for the *High Resilience Polyurethane* foam + polypropylene fabric without the official edge factor correction applied, compared with the corresponding earlier tests conducted without any edge frame. EF stands for no edge frame factor.

The reason for these different scaling factors is that the exposed horizontal window for irradiance is dependent on the horizontal area that the specimen 'sees' (the radiated energy from the cone heater). However once the sample has been ignited, the edge frame actually contributes to the heat flux felt by the specimen by re-radiation off the internal surfaces of its walls. It can also be thought of as a source of heat in its own right, absorbing and re-radiating the heat obtained from the Cone's heater element. The determination of the exact scaling factor to be used would be an interesting project to follow up. It is likely that a first approximation could be derived based on equating total heat release from a statistically appropriate size of the same constructed and weighted samples tested in both situations.

8.1.5 Comparison between CSIRO and the University of Canterbury

These show quite marked differences in behaviour, and are due to quite a range of possible reasons. The main one is different sample construction. The samples contained only slightly less fabric (about 2%), and although the polypropylene fabric has been shown to contribute quite sufficiently to the total heat release, the more dominant factor is how the fabric remains over the foam. For our samples the excess fabric edges were cut with the remaining tab glued firmly against the fabric against the side of the foam block. For CSIRO's samples the excess fabric was folded over against the side of the foam block and stapled. It is thought that the former construction produces a more rigid fabric cover, which will stay in place for longer. Other factors include different laboratory set ups, procedures and gas analysers. Although of small impact it is important to note that our samples were conditioned at 19^0C and 50% relative humidity, while CSIRO conditioned their samples at 20^0C and 65% relative humidity. **Table 8.1** discussed later in this section summarises the important parameter comparisons, while the graphs of the comparison HRR's are shown in **figures 8.22 – 8.25**.

8.1.5.1 *Standard Polyurethane* foam + polypropylene fabric

This is shown overleaf in **fig 8.22**, and it can be seen that very good agreement occurs between both these series of tests, in peak HRR, total heat released, duration of burning and similarity of HRR form.

8.1.5.2 *Standard Polyurethane* foam + cotton/linen fabric

This is shown overleaf in **fig 8.23**, and as can be seen a higher and much longer in duration peak HRR occurs for the University of Canterbury samples. Also of note is the location of the HRR trough and 2^{nd} peak which both occur very early and at quite a high level of HRR for the University of Canterbury's samples. This would suggest that the fabric was compromised very early in the test, (although in observations it generally appeared to remain intact until after 200 seconds had elapsed). The only other suggestions are aging of the fabric, reducing its' compactness thus allowing more airflow and holes (actually observed) forming in the fabric at the corners of the sample, due to the sharp and thin edges. For CSIRO's samples the fabric which was folded at the corners, provided extra cover and protection.

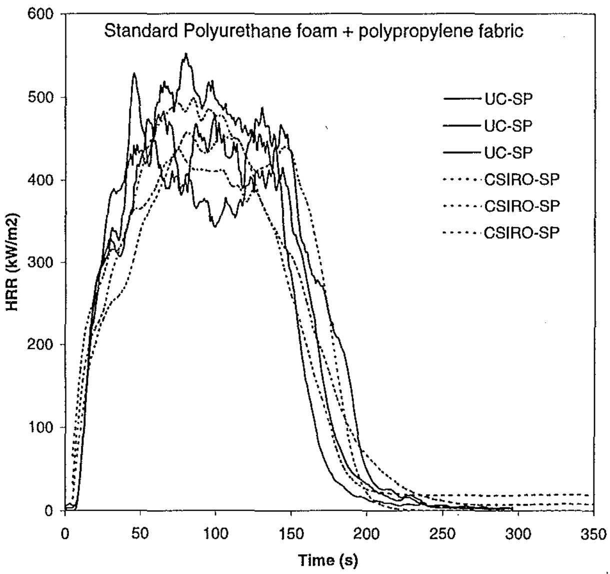

Figure 8.22 shows the HRR curves for *Standard Polyurethane* foam + polypropylene fabric comparing the Cone Calorimeter results between CSIRO (dotted line) and the University of Canterbury (solid line).

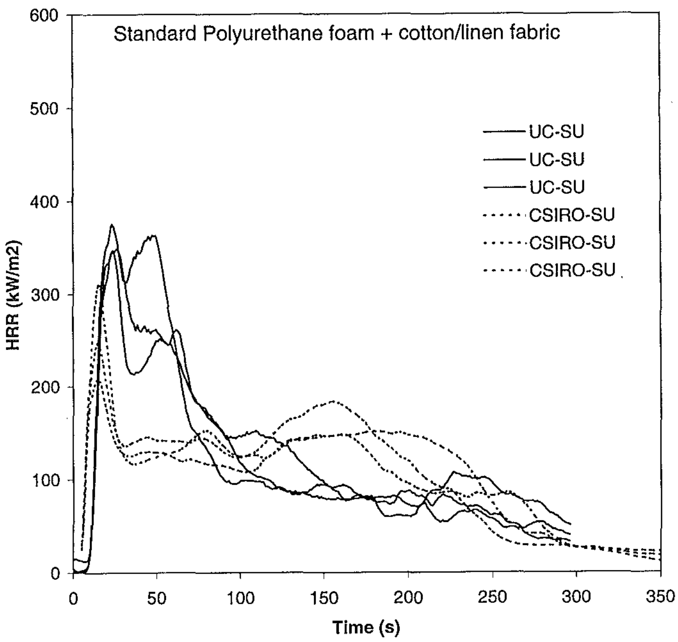

Figure 8.23 shows the HRR curves for *Standard Polyurethane* foam + cotton/linen fabric comparing the Cone Calorimeter results between CSIRO (dotted line) and the University of Canterbury (solid line).

8.1.5.3 *High Resilience Polyurethane* foam + polypropylene fabric

This is shown in **fig 8.24**, overleaf. The University of Canterbury samples exhibit a higher and longer in duration peak HRR. Also of note is the location of the not clearly defined HRR trough and 2nd peak with both occurring at quite a high level of HRR. The CSIRO samples on the other hand exhibit these parameters very distinctly and at a lower HRR. Apart from these factors there is a similar total amount of heat released and burn duration period.

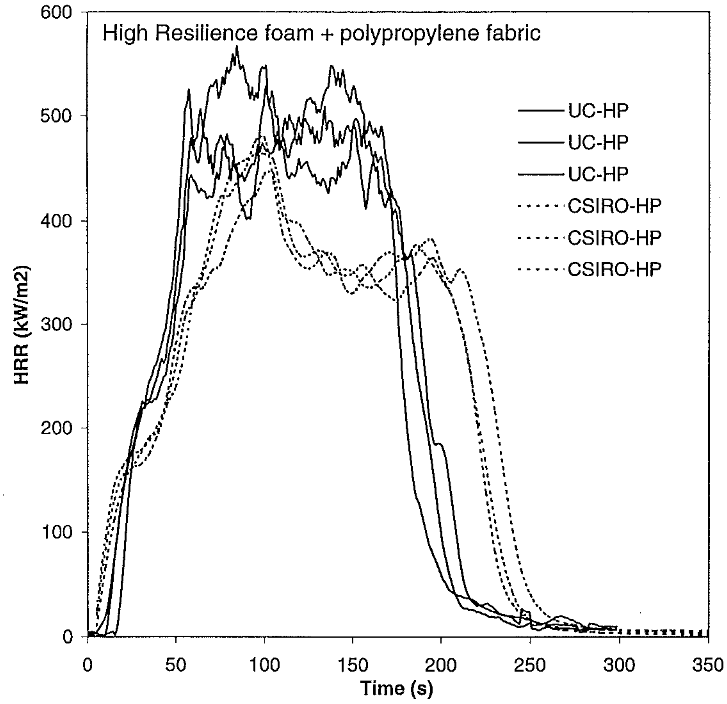

Figure 8.24 shows the HRR curves for *High Resilience Polyurethane* foam + polypropylene fabric comparing the Cone Calorimeter results between CSIRO (dotted line) and the University of Canterbury (solid line).

8.1.5.4 *High Resilience Polyurethane* foam + cotton/linen fabric

This is shown in **fig 8.25**, below. Although the general forms of the HRR curves are similar, the University of Canterbury samples are more time compacted. This would suggest that once again the heat generated by both the combustion reaction and cone heater degrades the fabric more quickly than those in CSIRO's tests. Aging effects of the fabric and fabric support at the corners are the most likely reasons for these observed differences.

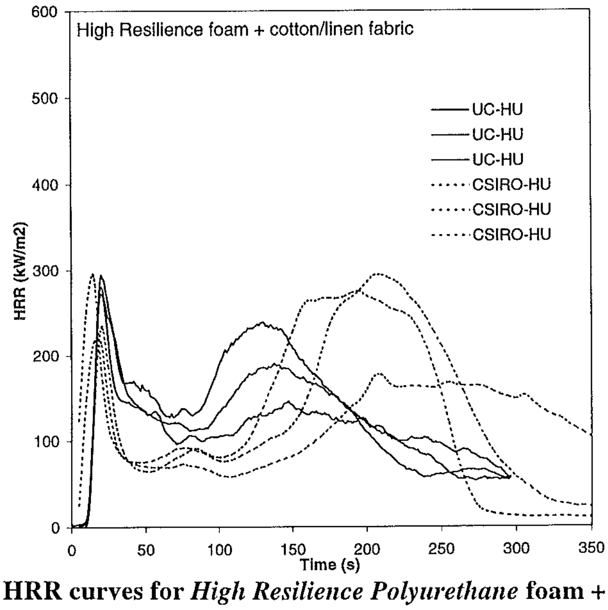

Figure 8.25 shows the HRR curves for *High Resilience Polyurethane* foam + cotton/linen fabric comparing the Cone Calorimeter results between CSIRO (dotted line) and the University of Canterbury (solid line).

8.2 CSIRO Furniture Calorimeter analysis of results

Although many different cushion combinations were tested, this analysis is confined just to the complete 1-seater, 2-seater and 3-seater series, which are described separately below.

8.2.1 Single seater series

8.2.1.1 Individual test triplicates of foam + fabric

This furniture series included the *Polypropylene & Cotton/Linen* fabrics and the *High Resilience, Standard Polyurethane, Enduro & Nolite* foams. Each fabric/foam combination was generally tested in triplicate, although for two combinations (*High Resilience* foam + polypropylene fabric & *High Resilience* foam + cotton/linen fabric) four tests were conducted. For clarity of comparison, the leading edges of the HRR curves within each test triplicate have been aligned (as ignition characteristics are not being studied in this report). Although it is possible to process this data further to obtain the degree of agreement and standard deviation between each individual test within a test triplicate; this has not been pursued. It is felt that a visual observation conveys the necessary information required. Should further processing be conducted, then HRR averages at set times (q_{120}, q_{180}, q_{300}) should be calculated and compared, similar to the CBUF prediction model. Only *total heat release*, *peak heat release rate* and *time to reach peak heat release rate* were compared, because of the difficulties associated with ignition characteristics.

These test triplicates are displayed in separate graphs in **figures 8.26 – 8.33**. From these figures one can see good agreement and repeatability within each test triplicate.

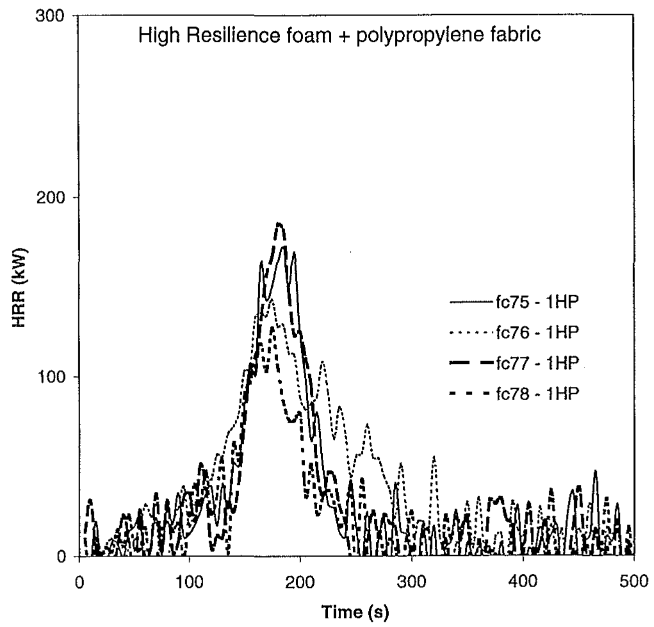

Figure 8.26 shows the full-scale Furniture Calorimeter HRR curves for the *High Resilience Polyurethane* foam + polypropylene fabric in the one seater chair style.

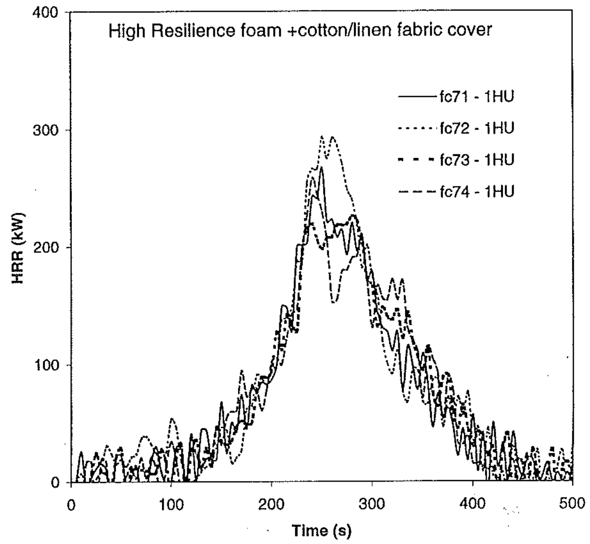

Figure 8.27 shows the full-scale Furniture Calorimeter HRR curves for the *High Resilience Polyurethane* foam + cotton/linen fabric in the one seater chair style.

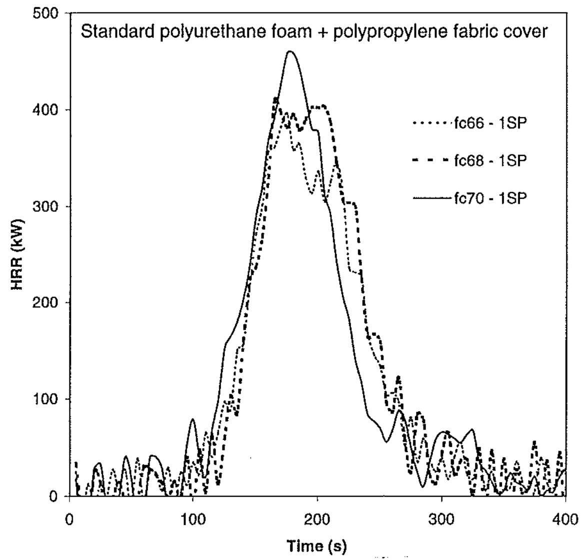

Figure 8.28 shows the full-scale Furniture Calorimeter HRR curves for the *Standard Polyurethane* foam + polypropylene fabric in the one seater chair style.

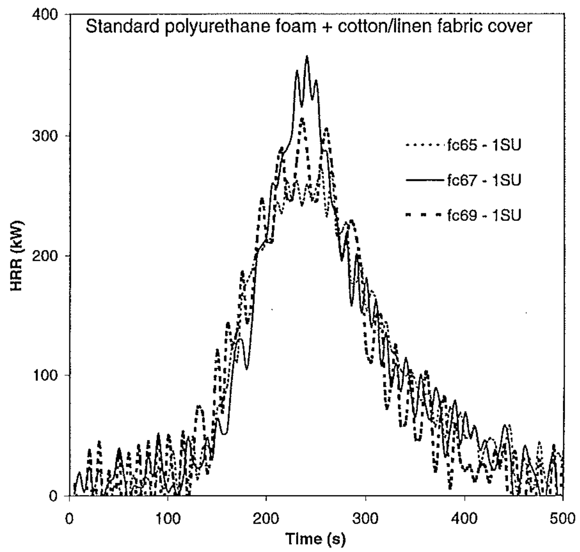

Figure 8.29 shows the full-scale Furniture Calorimeter HRR curves for the *Standard Polyurethane* foam + cotton/linen fabric in the one seater chair style.

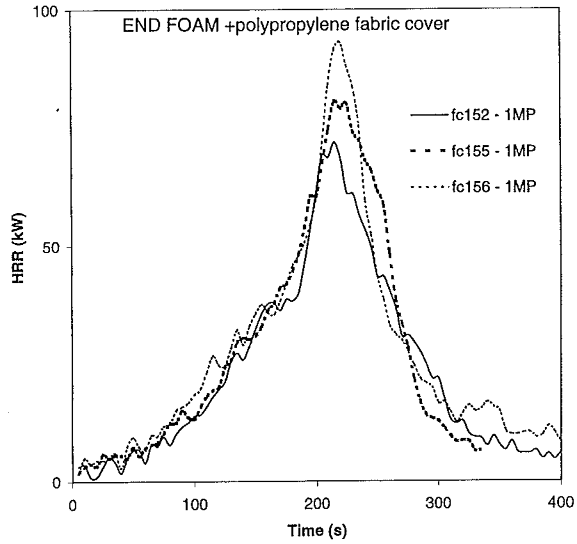

Figure 8.30 shows the full-scale Furniture Calorimeter HRR curves for the *Enduro Polyurethane* foam + polypropylene fabric in the one seater chair style.

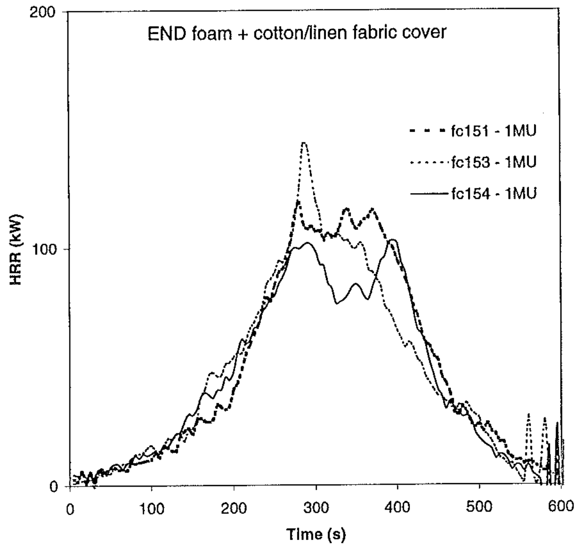

Figure 8.31 shows the full-scale Furniture Calorimeter HRR curves for the *Enduro Polyurethane* foam + cotton/linen fabric in the one seater chair style.

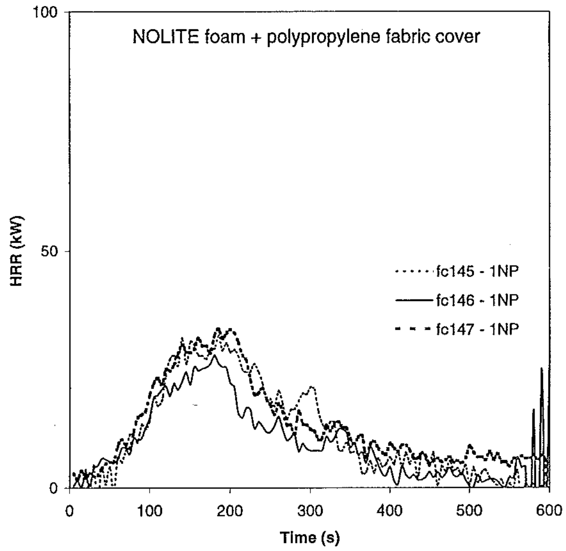

Figure 8.32 shows the full-scale Furniture Calorimeter HRR curves for the *NOLITE Polyurethane* foam + polypropylene fabric in the one seater chair style.

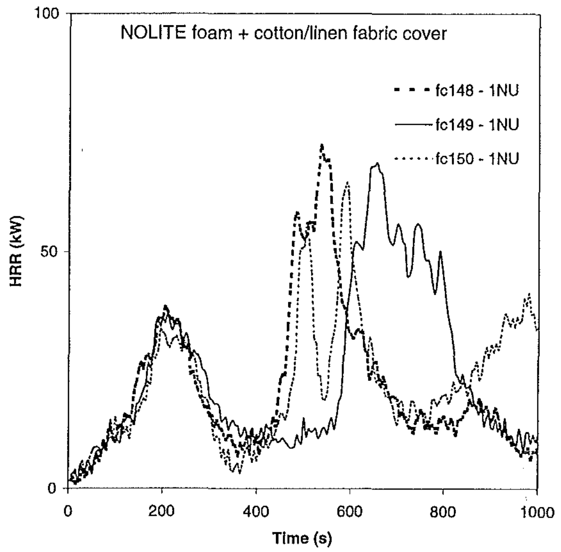

Figure 8.33 shows the full-scale Furniture Calorimeter HRR curves for the *NOLITE Polyurethane* foam + cotton/linen fabric in the one seater chair style.

Only for the more specialised foams *High Resilience, Enduro & Nolite,* do the HRR curves appear to vary slightly more widely, this is to be expected due to their higher fire resistance properties. Of the fabrics, polypropylene being 100% synthetic (which quickly melts away, exposing the foam underneath, when subjected to a direct heat source) shows slightly less variation, than the 100% natural-fibre cotton/linen fabric combination.

8.2.1.2 Comparison between fabrics for the same foam

These results are shown in **fig 8.34 – 8.37**. The polypropylene fabric is shown in the solid line whilst the cotton/linen fabric is the dotted line. Surprisingly in all but for the *Standard Polyurethane* foam, the cotton/linen fabric combination exhibits the highest peak heat release rate. This is attributed to the fact that these foams, (*High Resilience, Enduro* and *NOLITE*) are all speciality foams that have some degree of fire retardancy and thus need a wicking type material to aid in combustion. For the *Enduro* and *Nolite* foams, due to their high fire retardant additives, very minor sustained combustion occurs. On the other hand for the *Standard Polyurethane* foam, which has no fire retardant properties, the polypropylene fabric gives little to no protection, and a very high and sustained peak heat release rate is quickly reached. The corresponding cotton/linen fabric gives very good protection, resulting in a much lower, less severe fire.

The *High Resilience* foam illustrates very interesting behaviour. It appears that a critical heat flux must be reached before a self-propagating combustion reaction occurs. For this heat flux to be reached the ignition crib must remain intact for the duration of its' peak HRR. Unfortunately as the cotton/linen fabric only chars, but remains intact, the ignition crib remains intact on a stable surface and this required heat flux is reached. The polypropylene however melts away, and although the foam exposed below doesn't fully ignite into a self-propagating combustion reaction, it does sufficient melt and slump to topple the wood ignition crib, and disrupt its' peak HRR from being achieved.

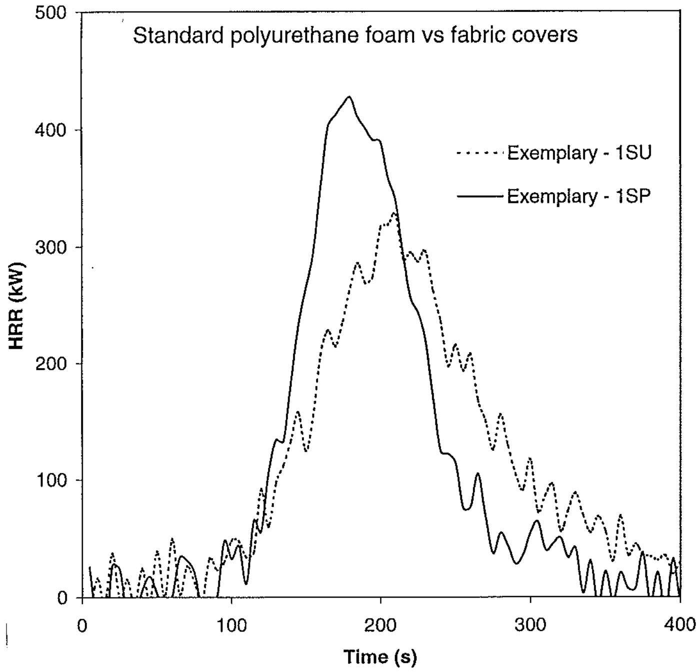

Figure 8.34 shows the HRR comparison curves (exemplary) between the two different fabrics for the *Standard Polyurethane* foam in the one seater series.

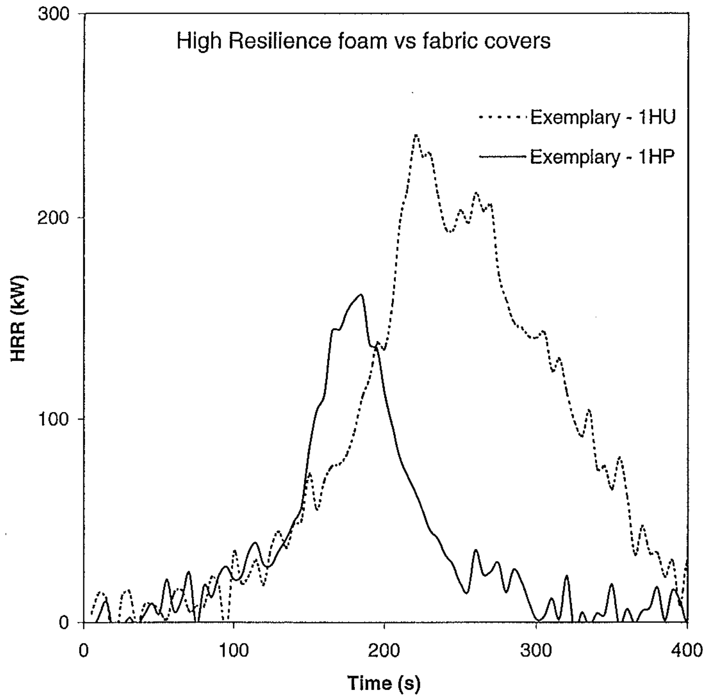

Figure 8.35 shows the HRR comparison curves (exemplary) between the two different fabrics for the *High Resilience Polyurethane* foam in the one seater series.

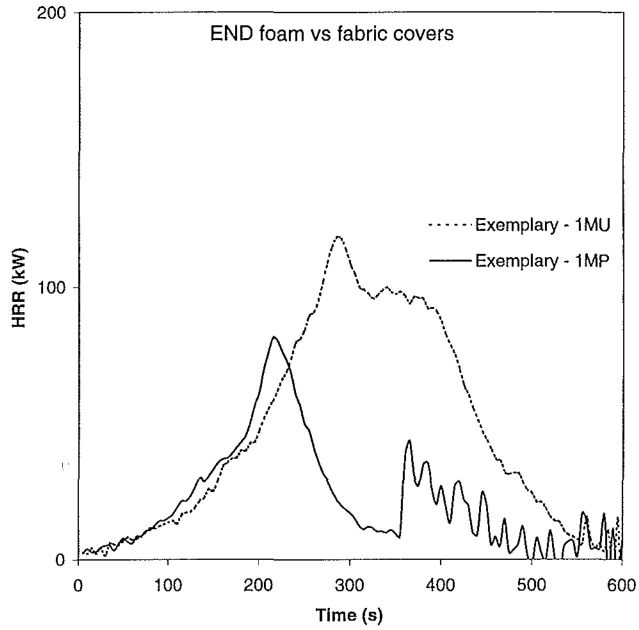

Figure 8.36 shows the HRR comparison curves (exemplary) between the two different fabrics for the *Enduro Polyurethane* foam in the one seater series.

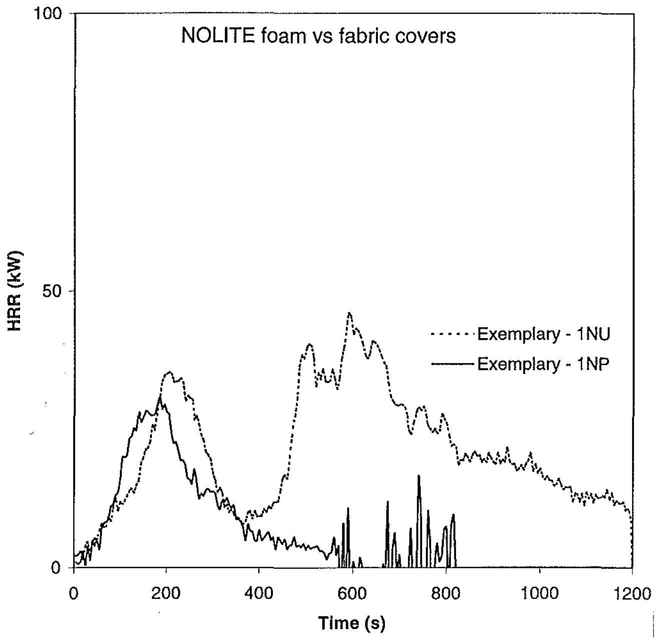

Figure 8.37 shows the HRR comparison curves (exemplary) between the two different fabrics for the *NOLITE Polyurethane* foam in the one seater series.

8.2.1.3 Comparison between foams for the same fabric

These results are shown overleaf in **figures 8.38 – 8.39**. In each fabric case the order of fire severity exhibited, from the highest foam down to the lowest is a reflection of its' relative fire retardant properties. *Standard Polyurethane* is the most severe, reaching the highest peak HRR in the shortest time and producing the greatest total heat released. It has the least density and contains no fire retardant properties. *High Resilience Polyurethane* foam is a distant second, being more dense than *Standard Polyurethane* and containing some fire retardancy.

Whilst the *Enduro* and *NOLITE* foams, which are denser still and contain high fire retardant properties, exhibit virtually no self propagating combustion behaviour at all.

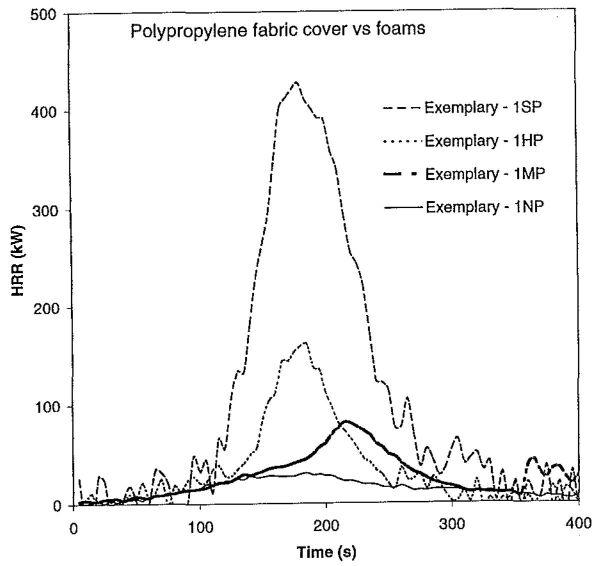

Figure 8.38 shows the HRR comparison curves (exemplary) between the four different foams for the polypropylene fabric in the one seater series.

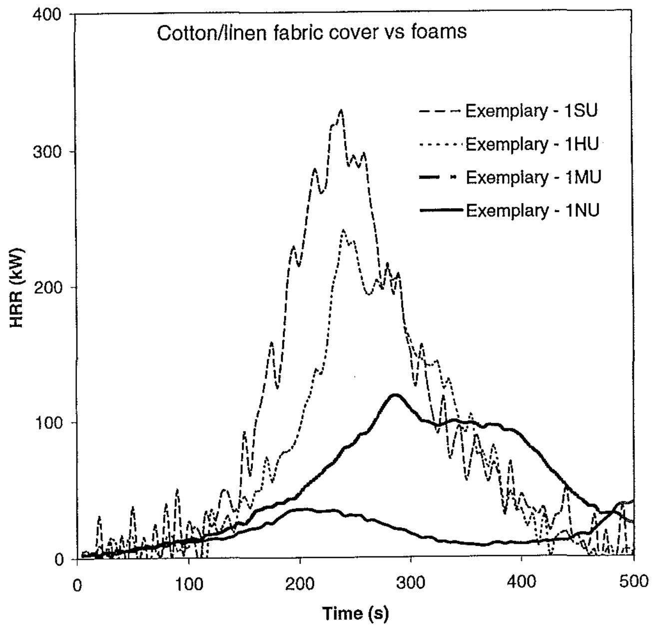

Figure 8.39 shows the HRR comparison curves (exemplary) between the four different foams for the cotton/linen fabric in the one seater series

Figure 8.40 overleaf shows the relative peak HRR's and duration of burning for the foam/fabric combination tests (exemplary curves have been shown for clarity) that is the main focus of this study. These are the *Standard* and *High Resilience Polyurethane* foams and the polypropylene and cotton/linen fabrics. As can be clearly seen the *Standard Polyurethane* foam + polypropylene fabric combination consistently exhibits the worst fire severity characteristics. The trends illustrate that the *High Resilience* foam delays and reduces the peak heat release rate, for both fabrics.

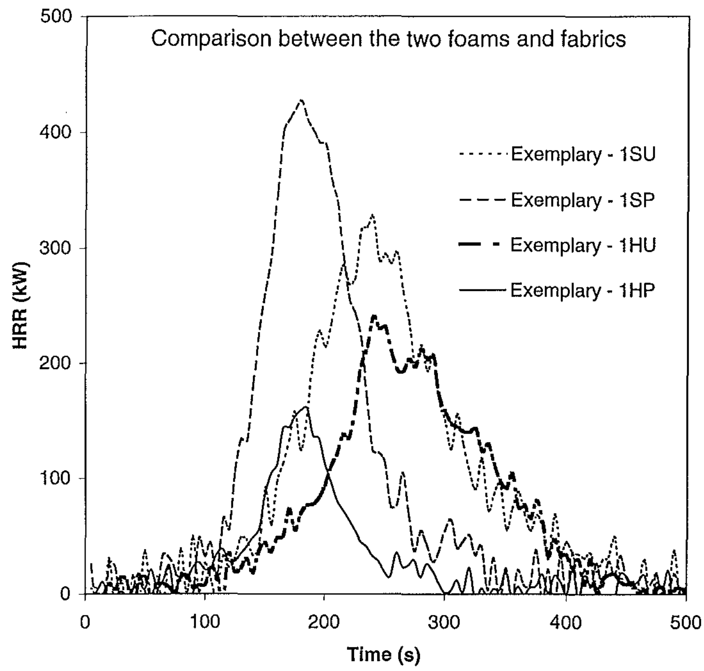

Figure 8.40 shows the HRR comparison curves (exemplary) between the two different foams and fabric in the one seater series.

8.2.2 Two seater series

This furniture series included the original *High Resilience & Standard Polyurethane* foams and *Polypropylene & Cotton/Linen* fabrics and again tests were conducted in triplicates for each fabric/foam combination. Unfortunately some data was lost from the original data, so cannot be displayed. The data that has been lost includes two test results from the *High Resilience* foam + polypropylene and one from the *High Resilience* foam + cotton/linen fabric combination. These test triplicates are displayed in **figures 8.41 – 8.44**. The leading edges of the HRR curves have been aligned within each test triplicate, for the purposes of making accurate comparisons and observations on the HRR, time to peak HRR and relative total heat release. These results vary quite considerably. For the purposes of clarity of comparison between the series, an exemplary curve has been chosen from each test triplicate. Invariably this is quite subjective, but for the purposes of being conservative, I have elected to choose the curve with the highest, or most sustained highest HRR.

The results obtained from the *High Resilience* + polypropylene (**fig 8.41**) and *High Resilience* + cotton/linen (**fig 8.42**) combinations don't appear to support sustained combustion. In fact for the former test, it would appear that ignition of the furniture specimen is only superficial. It is thought that the fluctuations in this HRR curve are due to noise amplification in the oxygen analyser. The results obtained from the *Standard Polyurethane* + polypropylene and *Standard Polyurethane* (**fig 8.43**) + cotton/linen (**fig 8.44**) give good correlation within the test triple, except for one outlier in each, which exhibits approximately half the peak HRR. It is interesting to note however that the burning duration of these two tests is similar.

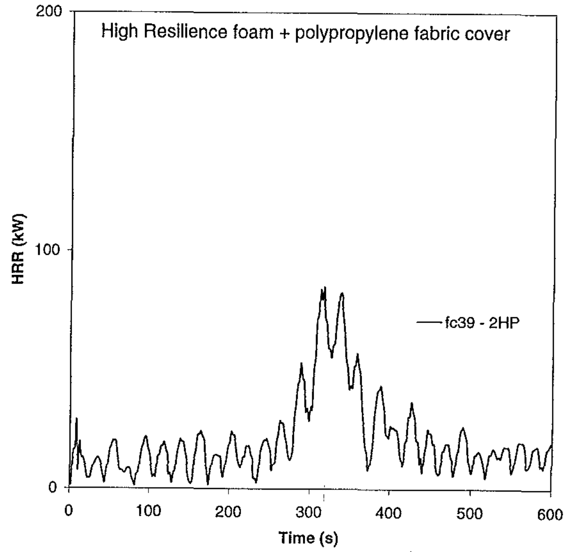

Figure 8.41 shows the full-scale Furniture Calorimeter HRR curve for the *High Resilience Polyurethane* foam + polypropylene fabric in the two seater chair style.

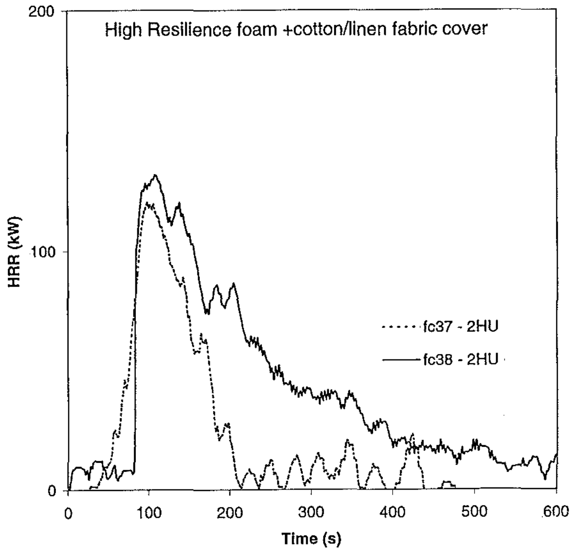

Figure 8.42 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + cotton/linen fabric in the two seater chair style.

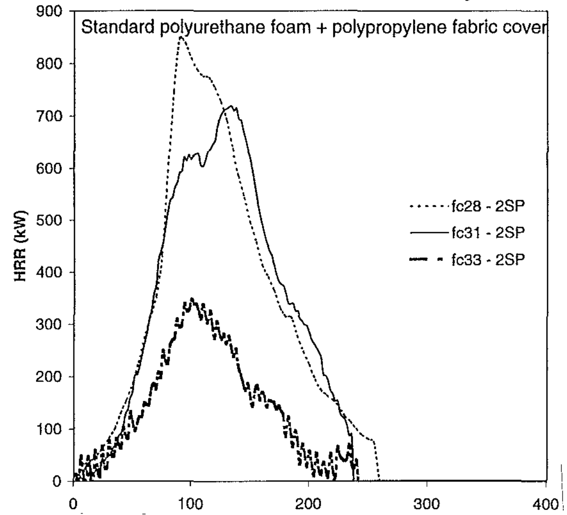

Figure 8.43 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + polypropylene fabric in the two seater chair style.

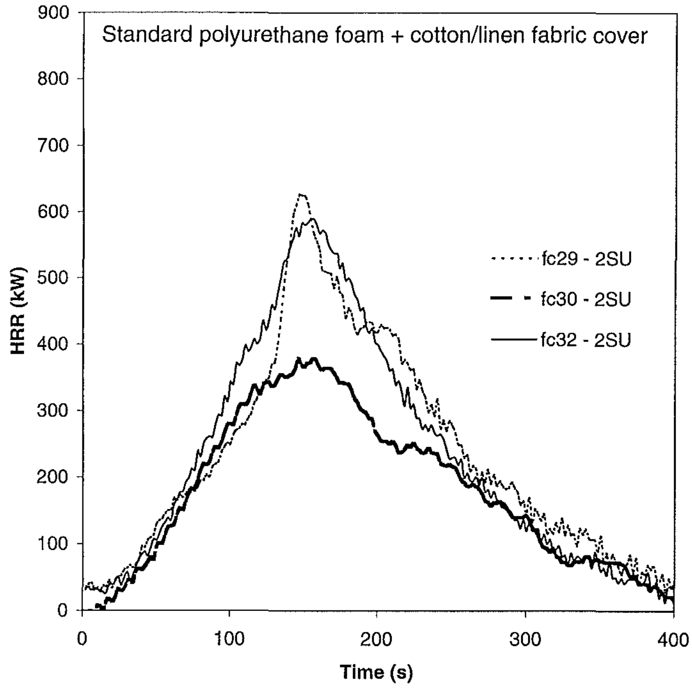

Figure 8.44 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + cotton/linen fabric in the two seater chair style.

8.2.2.1 Comparison between foams and fabrics

From these results which are shown in **fig 8.45** below, the *Standard Polyurethane* foam exhibits by far the most severe fire characteristics. Once again the polypropylene fabric is the worst when combined with the *Standard Polyurethane* foam. The cotton/linen fabric is not too far behind but its' peak HRR is smaller and of shorter duration.

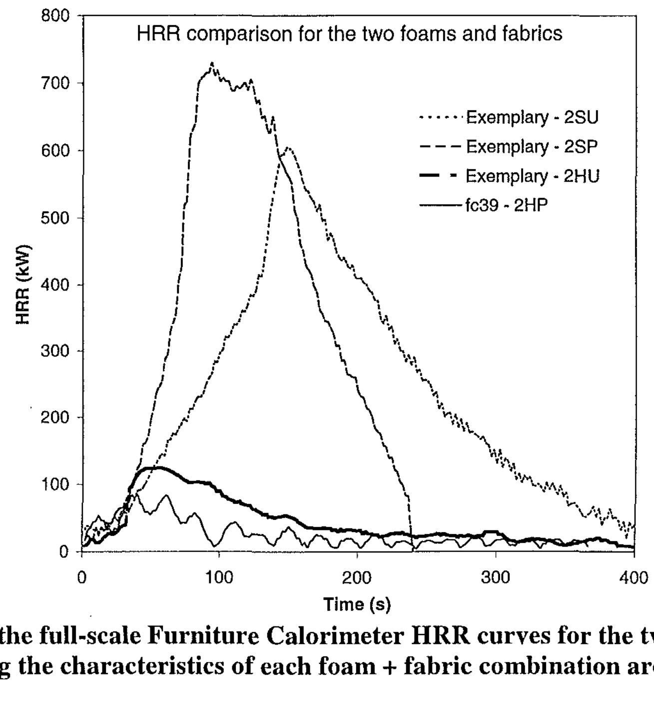

Figure 8.45 shows the full-scale Furniture Calorimeter HRR curves for the two seater chairs. Exemplary curves representing the characteristics of each foam + fabric combination are illustrated for comparison.

8.2.3 Three seater series

This furniture series included the same original *High Resilience & Standard Polyurethane* foams and *Polypropylene & Cotton/Linen* fabrics and again tests were conducted in triplicates for each fabric/foam combination. Unfortunately, only one test was conducted for the *High*

Resilience foam + polypropylene fabric combination. However the three-seater tests do contain a second series of the same tests with the ignition source located on the central seat cushion rather than the original right most cushion. These will be compared together, for the purposes of verifying the original data and seeing how the HRR and peak heat release rate are affected by the location of the ignition source. These results are shown below in **figures 8.46 – 8.49** for the ignition crib located on the right most seat cushion and **figures 8.50 – 8.53** for the ignition crib located on the central seat cushion. Both these test triplicate series show good repeatability, except for the *Standard Polyurethane* + polypropylene and *High Resilience* + cotton/linen combination both, with the ignition source located on the central seat cushion.

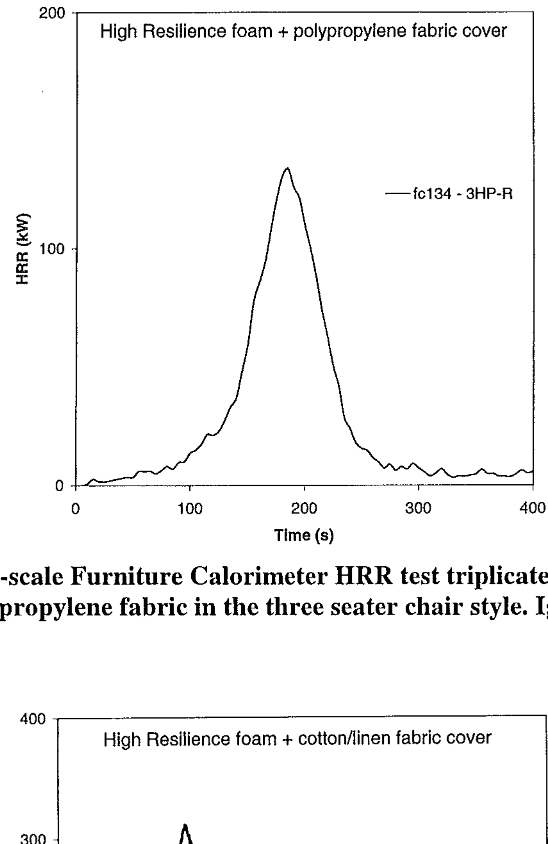

Figure 8.46 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + polypropylene fabric in the three seater chair style. Ignited on the right most seat cushion.

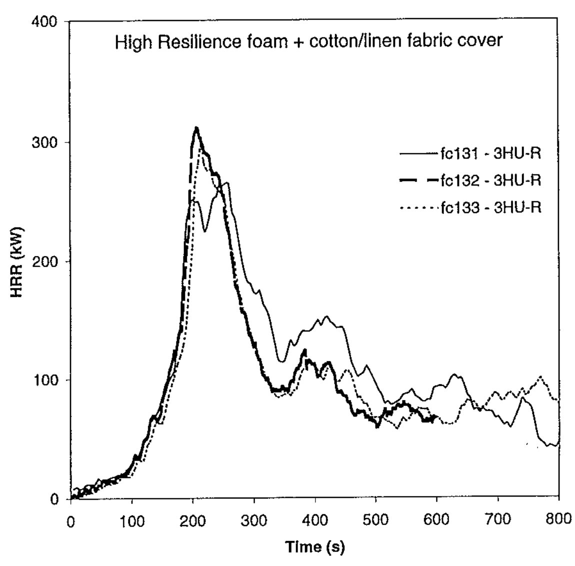

Figure 8.47 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + cotton/linen fabric in the three seater chair style. Ignited on the right most seat cushion.

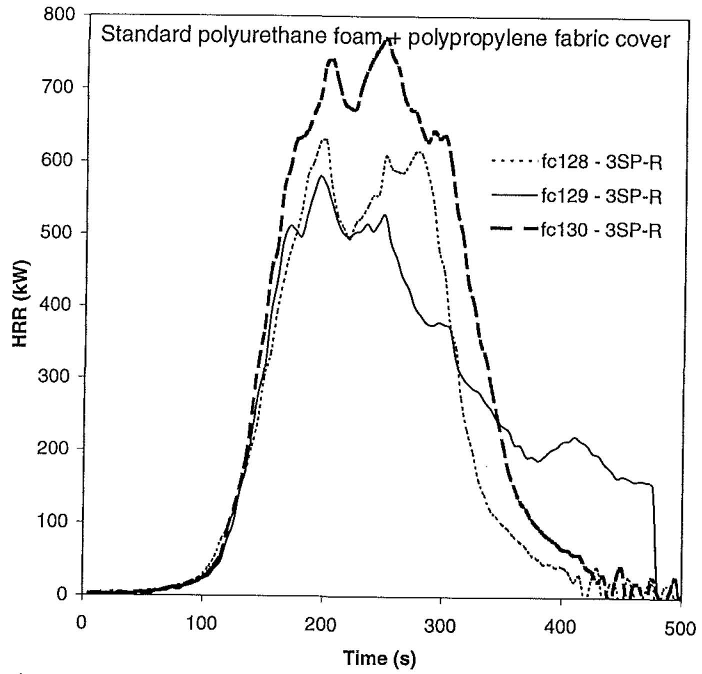

Figure 8.48 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + polypropylene fabric in the three seater chair style. Ignited on the right most seat cushion.

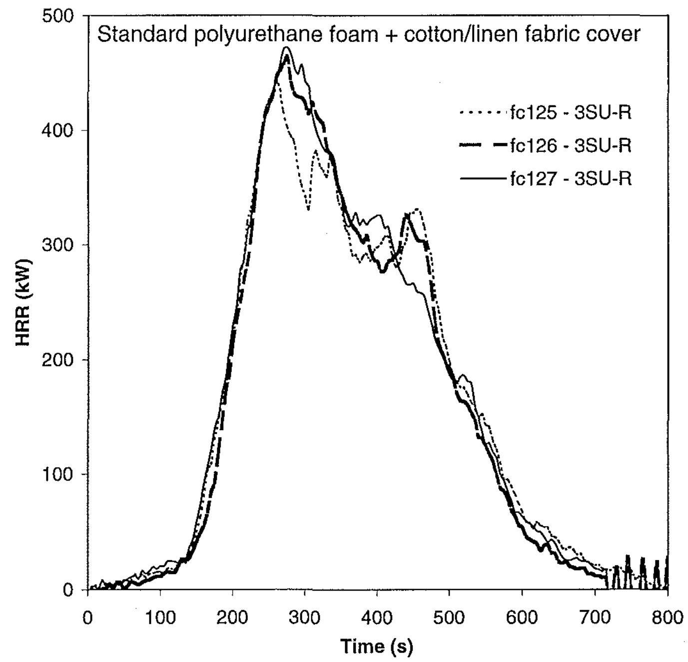

Figure 8.49 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + cotton/linen fabric in the three seater chair style. Ignited on the right most seat cushion.

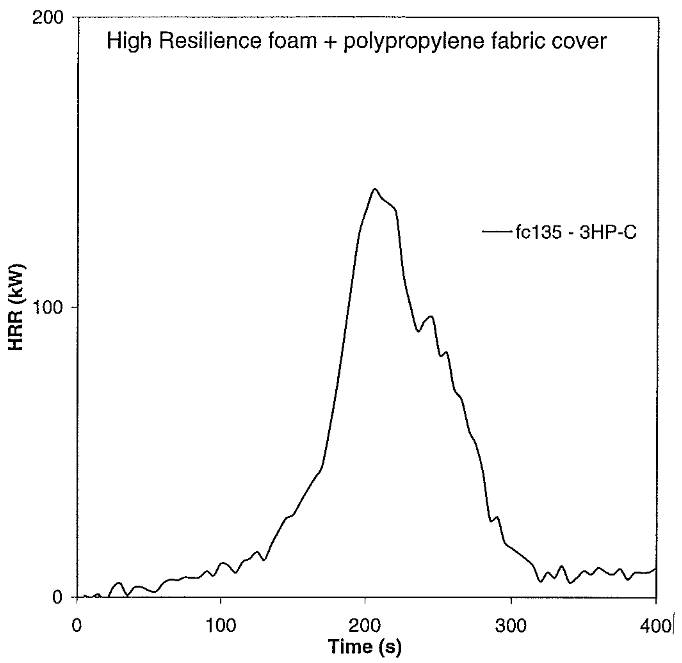

Figure 8.50 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + polypropylene fabric in the three seater chair style. Ignited on the central seat cushion.

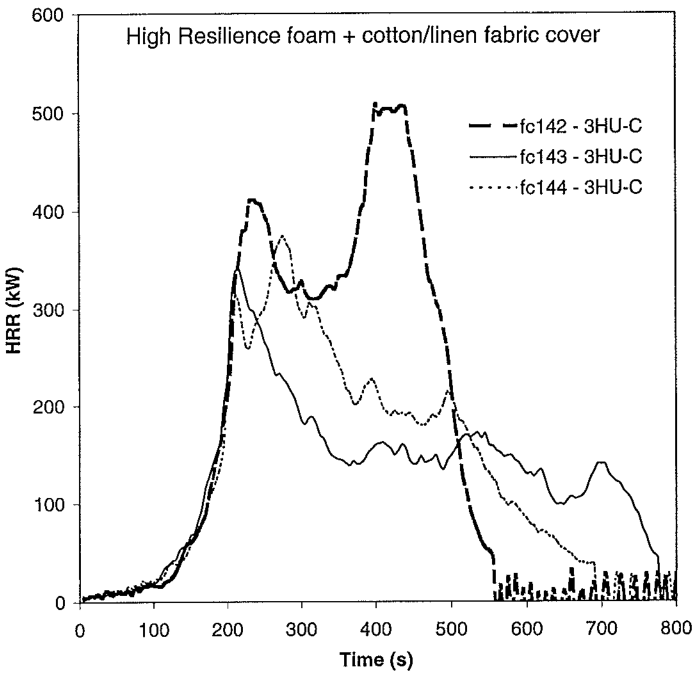

Figure 8.51 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + cotton/linen fabric in the three seater chair style. Ignited on the central seat cushion.

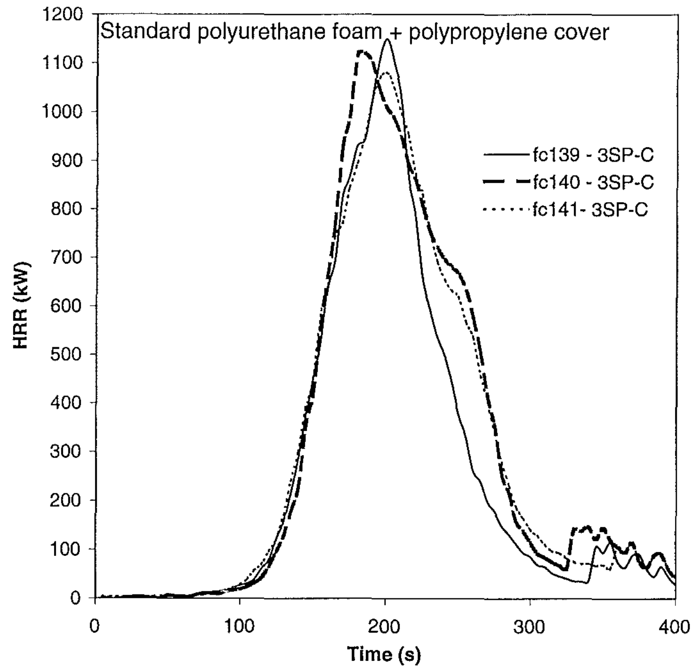

Figure 8.52 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + polypropylene fabric in the three seater chair style. Ignited on the central seat cushion.

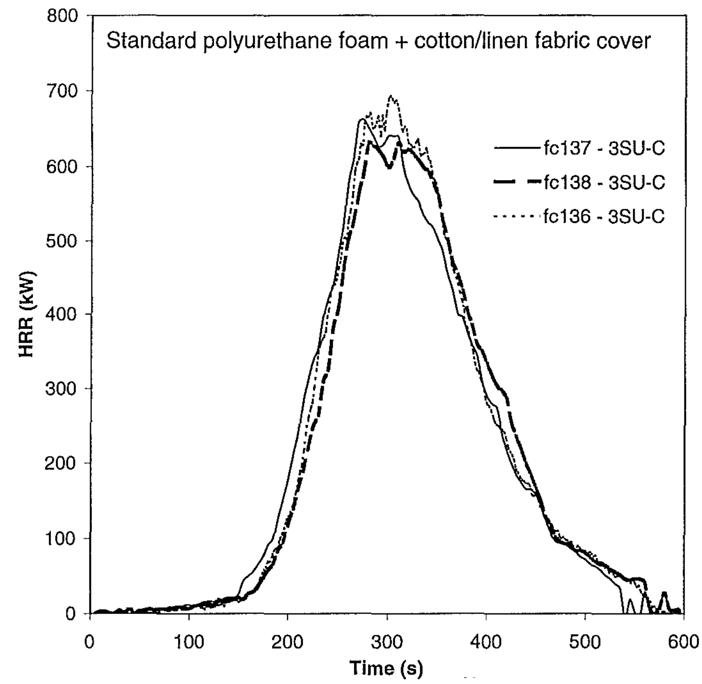

Figure 8.53 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + cotton/linen fabric in the three seater chair style. Ignited on the central seat cushion.

8.2.3.1 Ignition source location

Across all of the foam/fabric combinations the centrally located ignition source produced much higher peak HRR, while the ignition source located on the right most cushion produced longer burning, but lower peak HRR. This is a reflection on the flame spread characteristics of a centrally located ignition source which allows twice the number of directions for burning than an ignition source located on the end. These results are shown overleaf in **figures 8.54 – 8.57**.

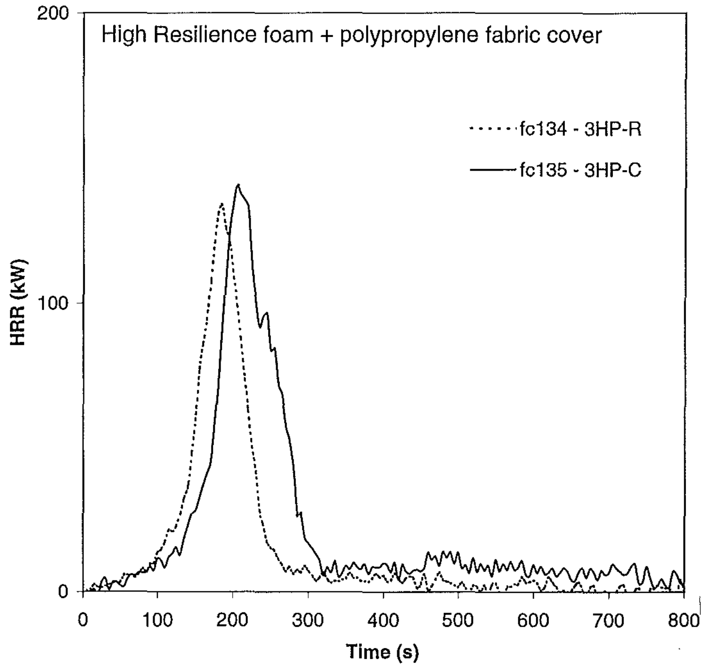

Figure 8.54 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + polypropylene fabric in the three seater chair style. Comparison is between the different ignition crib locations.

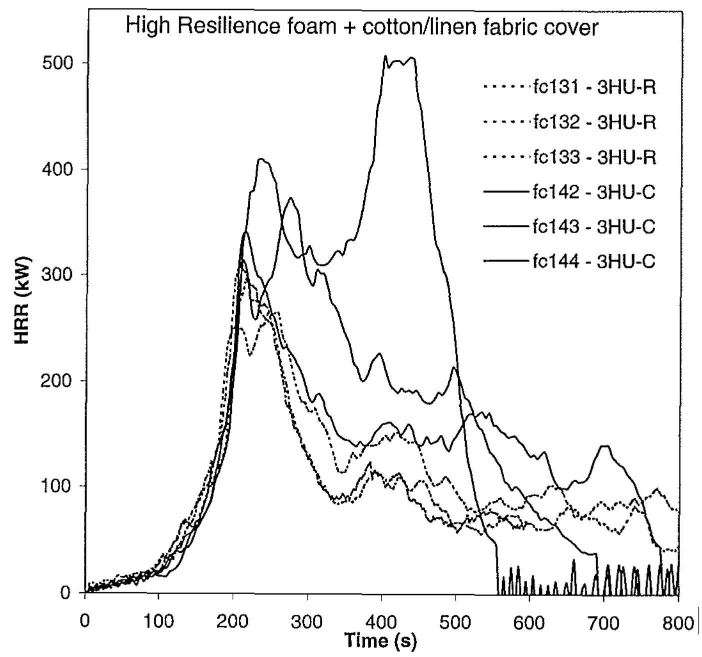

Figure 8.55 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *High Resilience Polyurethane* foam + cotton fabric in the three seater chair style. Comparison is between the different ignition crib locations.

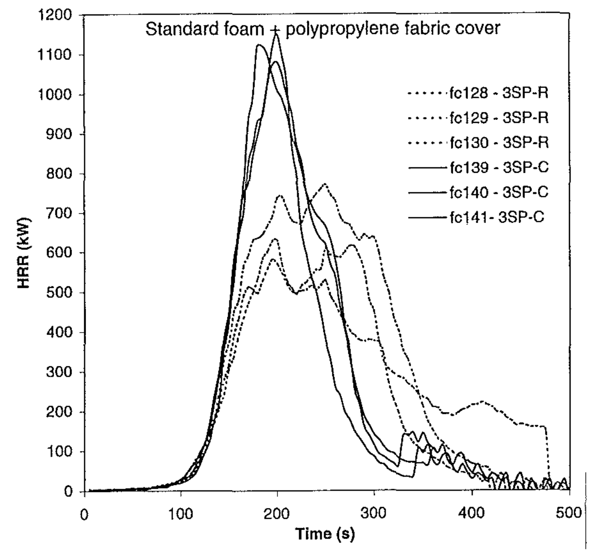

Figure 8.56 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + polypropylene fabric in the three seater chair style. Comparison is between the different ignition crib locations.

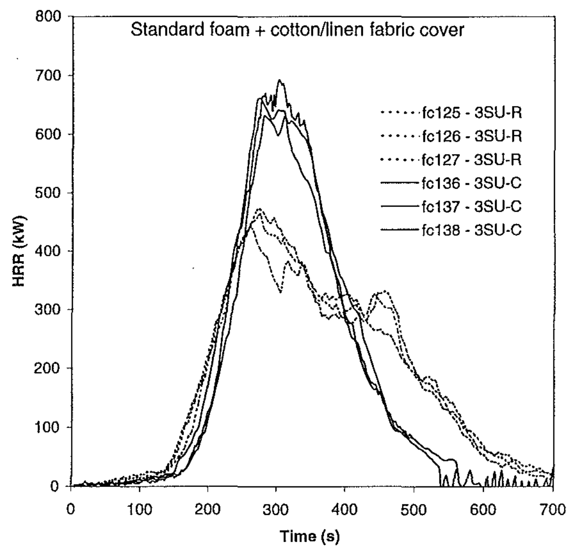

Figure 8.57 shows the full-scale Furniture Calorimeter HRR test triplicate curves for the *Standard Polyurethane* foam + cotton/linen fabric in the three seater chair style. Comparison is between the different ignition crib locations.

Once again it can be seen that while the *High Resilience* foam + cotton/linen fabric reaches a self-propagating combustion reaction, for both ignition locations, the *High Resilience* + polypropylene combination doesn't. The reasons for this are due to the fabric-foam interaction in conjunction with the steel sofa frame, and will be discussed in more detail later in this section.

Another visual marker in these HRR curves is the characteristic flame spread property that pertains to each fabric and foam. The right hand ignition source tests are the best illustration of this, with distinct troughs and strong second peaks (**fig 8.55 – 8.57**). From video observations the sofas with cotton/linen covered cushions exhibit fire propagation characteristics typical of a slow moving flame front, speed dictated by the charring rate of the fabric. For the polypropylene fabric covered cushions the flame spread is due more to radiation effects, (and the flammability of the foam) with the fire literally jumping over cushions as its' heat flux approaches the flash point of the foam.

Figures 8.58 – 8.59 show a comparison of the exemplary heat release rate curves for the foam/fabric combinations with each ignition location test series. As with the previous one and two seater specimens the order of fire severity ranges from *Standard Polyurethane* foam + polypropylene fabric which is the highest, then *Standard Polyurethane* foam + cotton/linen fabric, then *High Resilience* foam + cotton/linen fabric to *High Resilience* foam + polypropylene fabric, which is the lowest.

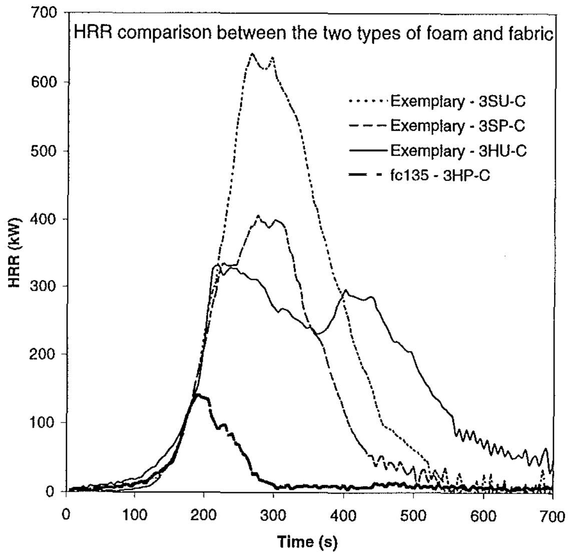

Figure 8.58 shows the full-scale Furniture Calorimeter HRR exemplary curves for the three seater chairs with Ignition crib located on the central seat cushion.

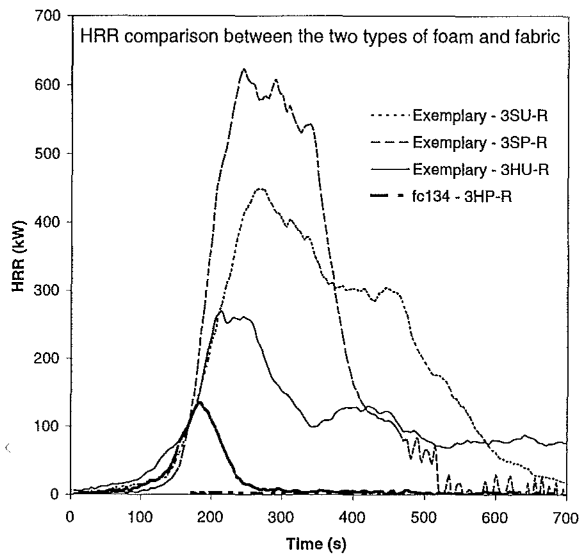

Figure 8.59 shows the full-scale Furniture Calorimeter HRR exemplary curves for the three seater chairs with Ignition crib located on the right most seat cushion.

8.2.3.2 Cross comparison between the one, two and three seaters

These results are important in that they allow a visual check that the test results are consistent with what would be expected (although no results have been rejected for the sake of conformity). This expectation is that as we increase the sofa size (number of cushions) from one to two to three seats, we expect a higher and longer in duration peak HRR. As can be seen in the results shown below in **figures 8.60 – 8.63.** For the three seater series with right seat ignition source, this is indeed the case, with the three seaters in each of the self-propagating cases exhibiting much longer burning duration's, with high HRR's. The three seater series with the centrally located ignition source, also produced longer in duration fires, but were most distinguished in that they had substantially higher HRR's than either the one, two or three seaters (right most seat cushion ignited).

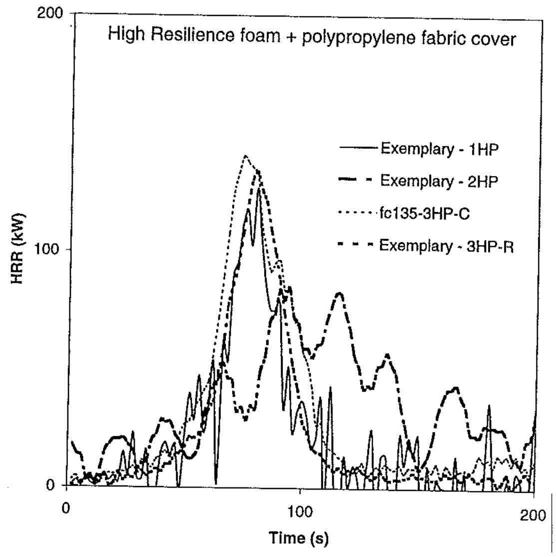

Figure 8.60 shows the full-scale Furniture Calorimeter HRR exemplary curves for the *High Resilience* foam + polypropylene in the one, two and three seater chairs (both ignition crib locations) series.

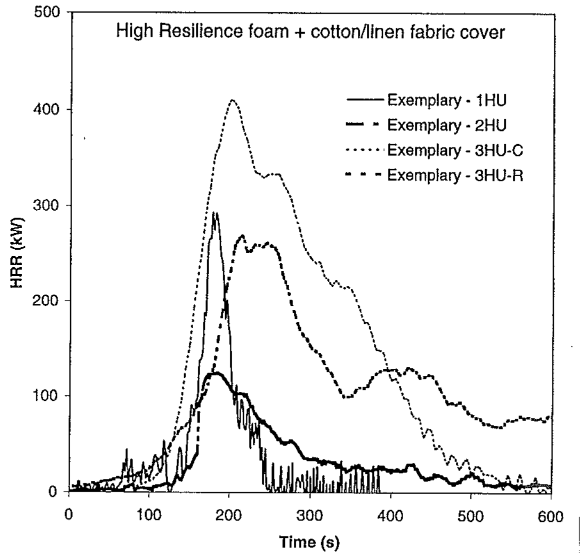

Figure 8.61 shows the full-scale Furniture Calorimeter HRR exemplary curves for the *High Resilience* foam + cotton/linen fabric in the one, two and three seater chairs (both ignition crib locations) series.

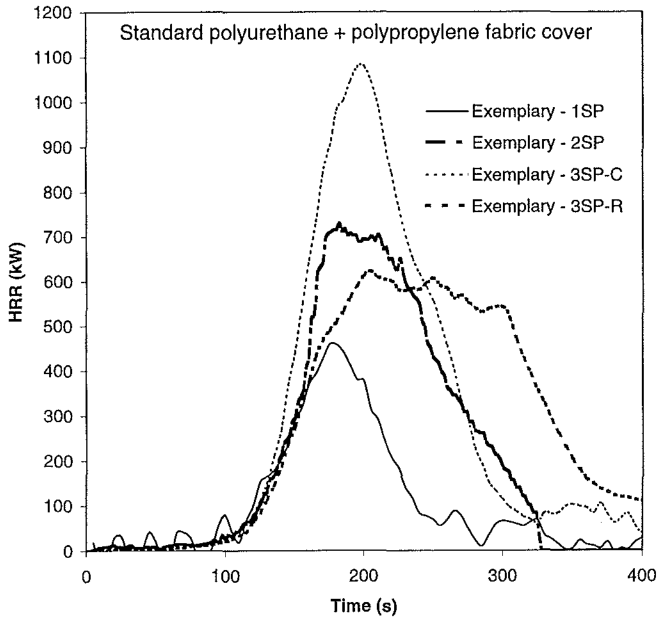

Figure 8.62 shows the full-scale Furniture Calorimeter HRR exemplary curves for the *Standard Polyurethane* foam + polypropylene fabric in the one, two and three seater chairs (both ignition crib locations) series.

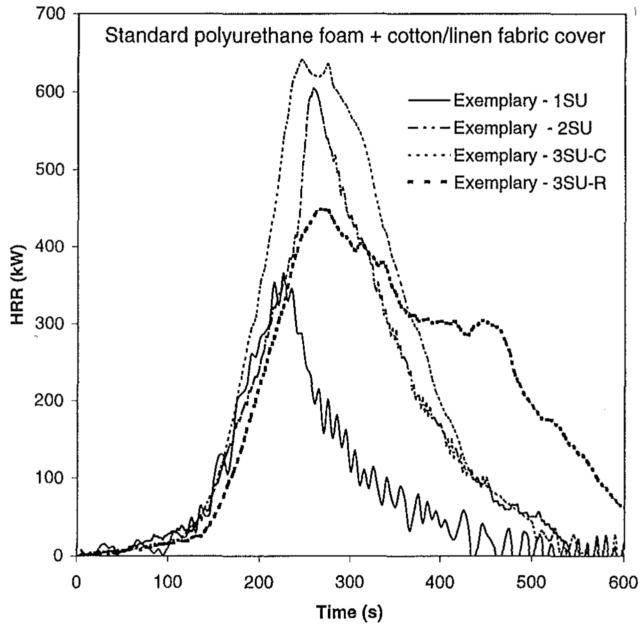

Figure 8.63 shows the full-scale Furniture Calorimeter HRR exemplary curves for the *Standard Polyurethane* foam + cotton/linen fabric in the one, two and three seater chairs (both ignition crib locations) series. R = right hand ignition located. C = centre located ignition source

8.2.3.3 Ignition source

This was a characterised 400g wood crib, but the concerns raised are that its' characteristic HRR curve cannot be easily subtracted from that of the furniture specimen's, due to the fact that its' HRR increases as the furniture specimen's HRR grows – both feeding each other increasing levels of heat flux. This in the end becomes an academic question as ignition characteristics are outside the scope of this report. Suffice it to say that its' percentage contribution to the total heat release is, in the majority of furniture tests, very small.

8.2.3.4 Steel sofa frame

Using the same non-combustible sofa frame for all of the tests does have the advantage of eliminating it from contributing to any observed variations in the observed results. However the design of the steel sofa frame, did contribute in a significant manner to all of the observed results. And it is the considered opinion of the author that this contribution was in a biased fashion (generally causing a reduction in the HRR), not truly representative of what one would expect from the fire load present in the cushions. The problem lies in the large gaps between the steel structural supports and seat cushion support mesh. In most standard furniture of this design there is cloth wrapping under the seat cushions and back cushions. This has the effect of containing any fire for a longer time period in the middle of the burn zone, keeping the generated heat flux radiant on the areas adjacent to those already burning – the fire as a result exponentially grows. In the case of the metal mesh under the seat cushions, the melting foam quickly dripped through it to the floor, where unless sufficient heat flux ignited it, it remained unburnt. For the *High Resilience* foam, which required a higher heat flux to raise it to its latent heat of vaporisation, the melted foam must be contained close to the wood ignition crib and already burning parts of the furniture. When combined with the cotton fabric (see **fig 8.60**) which charred, but remained intact for longer, this wasn't such an observed issue. However when in combination with the polypropylene fabric (see **fig 8.61**), which also melted, the furniture combustion reaction more or less ended when the ignition crib finished burning. From observations most of the foam around the ignition crib and surrounding areas melted away, having run through the bottom of the seat cushion to lie unburnt on the floor.

8.2.3.5 Video footage observations

Each test was fully documented with video footage. This included a split screen recording, displaying right and left of centre camera angles, during the ignition and propagating phases of the fire. These video recordings were invaluable in that visual observations of furniture tests that appeared low in peak HRR and or total heat release could be made and compared with the other tests conducted in the series. Other important issues also emerged, from the video recordings providing immense insight into the role that fabric plays in its' relationship with foam in the combustion behaviour of upholstered furniture.

Although it is hard to quantify the exact size of a fire, based just on visual observation, it is a useful indicator as a measure of comparison with other similar fires. The tests conducted on the two-seater series are an excellent example of this. Several of these tests were very low in comparison with the other test triplicates, reaching a peak HRR of about half of what would be expected, based on the other tests, and the exhibited burning behaviour in the corresponding single-seater series. When these tests were reviewed on video, it does appear that the expected heat release should have been higher. This applies especially to tests:

FC39	High Resilience foam + polypropylene fabric cover
FC38 & FC37	High Resilience foam + cotton/linen fabric cover
FC33	Standard Polyurethane foam + polypropylene fabric cover
FC30	Standard Polyurethane foam + cotton/linen fabric cover

These tests were all conducted in sequence within the space of 7 days, with FC37-39 being tested all on the 6th April, so it is possible that, events unknown, contributed to give lower than expected heat release and peak HRR values.

8.2.3.6 Observations of the fabric and foam interaction

Of at least equal significance from the video recordings were the displays of how the fabric interacted with the fire. This interaction occurred in distinct ways and was different for the two types of fabric used. In considering the case of the fabric in isolation from the foam the two fabrics were characterised by quite different behaviour.

The cotton/linen fabric chars when subjected to heat, but generally remains intact, (protecting the foam from the fire), until it is of sufficient size to generate the heat flux required to render the cloth fibres apart. The polypropylene fabric on the other hand, quite quickly shrinks and melts, when subjected to flames, exposing the foam underneath. These quite different fabric behaviours at opposite ends of the spectrum produced equally opposite results when combined with the foam. For foam that was very vulnerable to fire attack, such as the Standard Polyurethane, any protection was better than no protection. The polypropylene, which quickly shrinks back, when subjected to fire splitting and melting as it does, so, exposes whatever lays below it. As a result this fabric/foam combination produced the highest, fastest and most intense heat release rates. The cotton/linen combination however, delayed the fire from any direct attack on the foam and so smaller but longer in duration heat release rates were obtained. The converse appears to be true when examining the High Resilience foam. Here the foam is denser and contains fire-resisting additives, both of which offer some protection from fire. However when in combination with the cotton/linen fabric, which is traditionally viewed as being of superior fire performance due to its' charring properties, actually contributed to a more severe fire. This initially appears the least likely of results that one might have expected, but when viewed within the context of the fabric, furniture frame style, burning location and ignition source characteristics a possible explanation results. Because the fabric stays in place, the ignition source remains intact for longer, atop a pile of melted foam. The cotton, then acts in much the same way as a wick, increasing the surface area to volume ratio of the exposed fuel, so that effective volatilisation can occur. The polypropylene on the other hand melts away and along with the exposed foam, which also melts, drips onto the floor, where it remains unburnt, unless the combustion reaction above generates sufficient heat to volatise it. Furthermore the ignition crib tends to fall through the melted fabric, foam and steel mesh sofa frame to the floor below, thus removing the main heat source from the combustion reaction. In several of the tests sufficient heat was still generated from the fallen ignition crib embers below to melt the foam above and provide a steady supply of fuel, although the combustion reaction was very much reduced. It was interesting to note that the High Resilience foam in a melted pool below the burning specimen only ignited when the fire above was raging (providing sufficient heat flux for combustion), or a wicking material, such as the ignition crib embers were present.

8.2.3.7 Flame spread

Flame spread was also very fabric dependent. The cotton/linen fabric, by charring, protects the foam, but in so doing also acts like a wick, sustaining an otherwise potential pool fire. Because the bulk of the melted foam, remains mostly in the sofa, encased in the charred cotton/linen fabric shell, the combustion reaction steadily grows, albeit at an initially slower rate. The polypropylene which melts, only exposes the foam which depending on its' fire resisting properties determines whether a self-propagating fire occurs – in the case of the High Resilience foam + polypropylene fabric this is not usually the case.

8.3 Predicted full-scale results using model I from CBUF

These results are based on particular criteria as obtained from the Cone Calorimetry tests. These criteria relate to the HRR 1st and 2nd peaks, HRR troughs, effective heats of combustion and ignition times that were acquired from the samples, during a test. Two separate cone tests (CSIRO & UC) were conducted and both were applied to the CBUF model for comparison with the full-scale results. In addition to this a further test series was conducted on one of the samples (High Resilience foam + polypropylene fabric) at three different heat flux irradiances, using an edge frame. The cone samples prepared via appendix 6A as outlined in the CBUF report are thought to be the most relevant to this study, as the correlations in *Model*

I are specifically constructed from statistical results based on this protocol. However all three will be compared. The analysis of these results will focus on the separate foam + fabric combinations as each correlation graph has the predicted results plotted from both cone tests. Each graph also contains the predicted versus the actually measured full-scale results for the single, two, three (right hand ignition source) and three-centre ignition source. It is important to note that due to the ignition source characteristics the time to reach peak heat release rate is started from when the full-sized furniture specimen exceeds 50 kW. Due to the quite widely varying ignition characteristics observed, this measurement is thought the least reliable indicator of hazard.

8.3.1 Standard Polyurethane foam + polypropylene fabric

The results for these correlations are shown in **figures 8.64 – 8.66**. This series gives very good accuracy between the predicted versus measured fire parameters.

8.3.1.1 Peak heat release rate

This comparison is shown below in **fig 8.64**. Both the CSIRO and University of Canterbury (UC) predictions based on their respective cone tests give very close and similar results to those actually measured for all of the single seaters, two of the two seaters and all of the 3-centre ignited three seaters. The right hand ignited (3R) three seaters, which has reduced capability for flame spread gives a very poor comparison, being substantially lower than predicted, which is expected.

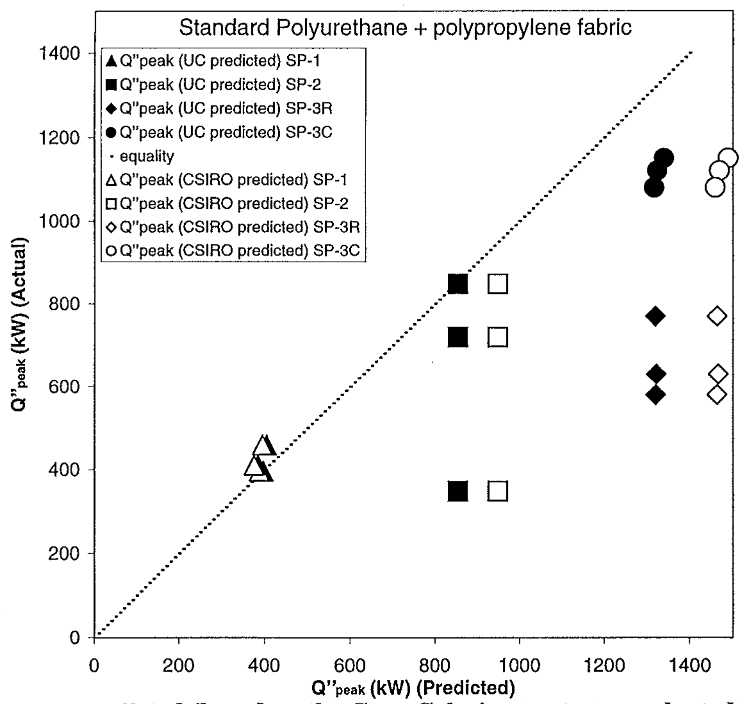

Figure 8.64 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) peak HRR.

8.3.1.2 Time to reach peak heat release rate

Both the CSIRO and UC results give very close comparison to those actually measured in the Furniture Calorimeter. One of the centre ignited three seaters' displays a much longer than predicted time to reach peak heat release rate. This is illustrated below in **fig 8.65**.

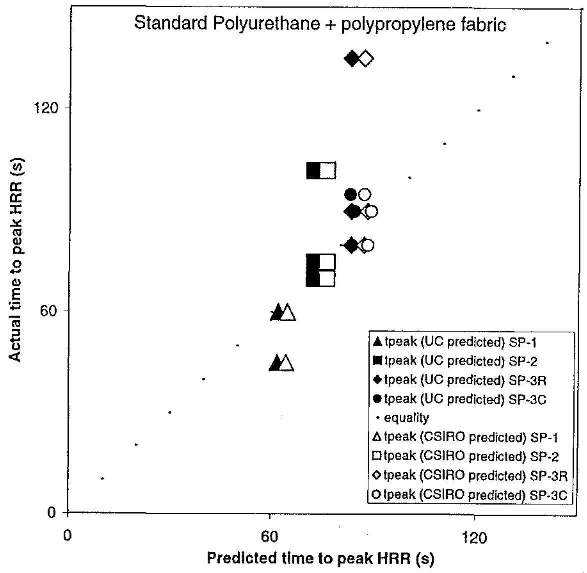

Figure 8.65 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) time to reach peak HRR (this time criterion starts once the HRR has exceeded 50 kW).

8.3.1.3 Total heat released

These results are shown in **fig 8.66,** and illustrate that for all but the CSIRO centre ignited three seaters, the predicted results show a very good comparison. Of more importance is that all lie below the equator line and are thus conservative predictions. The UC predicted results do show a much closer approximation.

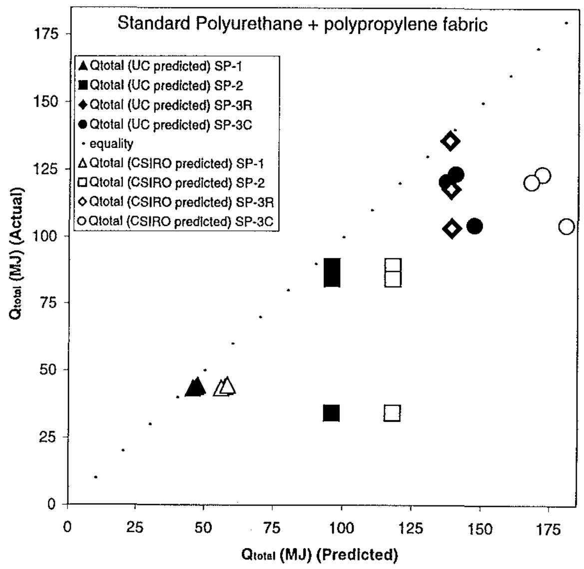

Figure 8.66 shows the predicted (based on the Cone Calorimetry tests from both at CSIRO & University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) total heat released.

8.3.2 Standard Polyurethane foam + cotton/linen fabric

The results for these correlations are shown in **figures 8.67 – 8.69**. This series gives average accuracy between the predicted versus measured fire parameters.

8.3.2.1 Peak heat release rate

This comparison is shown in **fig 8.67**. The CSIRO predictions give a much better comparison with the measured values, although the predictions from the UC cone results for the two and three seaters are also good. The right hand ignited (3R) three seaters, exhibits lower than predicted peak heat release rate, which is expected due to reduced opportunity for initial flame spread.

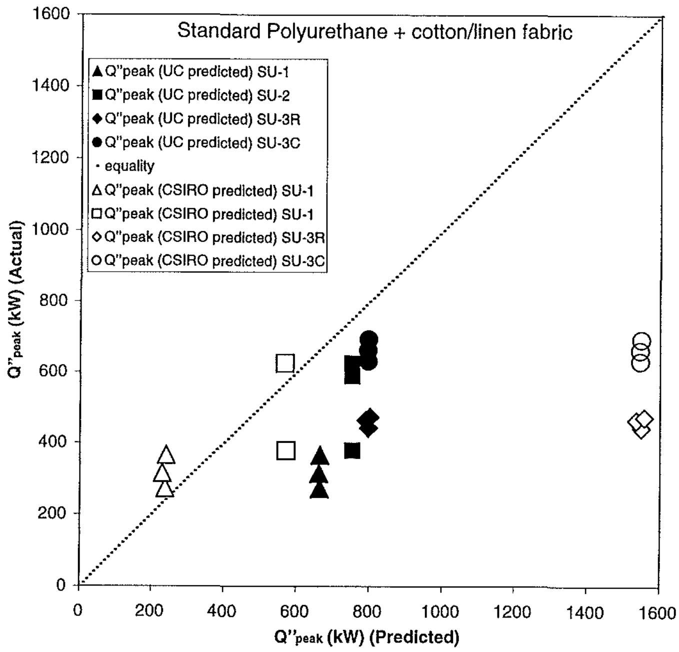

Figure 8.67 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) peak HRR. This is for the *Standard Polyurethane* foam + cotton/linen fabric.

8.3.2.2 Time to reach peak heat release rate

This comparison is shown below in **fig 8.68**. The measured values for time to reach peak heat release rate are all around the 120-second mark. The UC predictions appear to predict this time the most accurately. CSIRO predictions are all unsafe as they under predict the time to reach peak hazard.

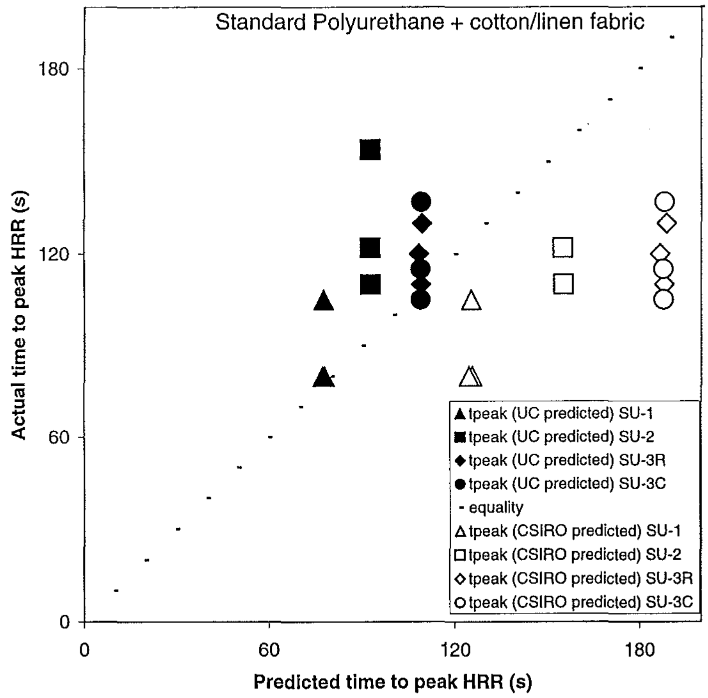

Figure 8.68 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) time to reach peak HRR (this time criterion starts once the HRR has exceeded 50 kW).. This is for the *Standard Polyurethane* foam + cotton/linen fabric.

8.3.2.3 Total heat released

For both the CSIRO and UC predictions, a very good comparison with the measured values occur. Although most do appear slightly above the equator line and are thus slightly on the under conservative side. The CSIRO predicted results do show a slightly closer approximation. These results are shown in **fig 8.69**.

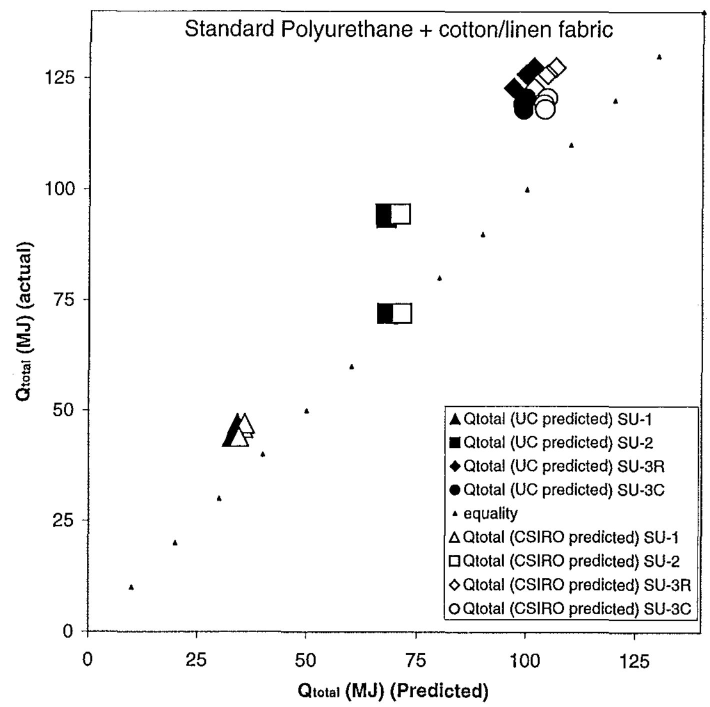

Figure 8.69 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) total heat released. This is for the *Standard Polyurethane* foam + cotton/linen fabric.

8.3.3 High Resilience foam + polypropylene fabric

The results for these correlations are shown below in **figures 8.70 – 8.72**. This series gives very poor accuracy between the predicted versus measured fire parameters. This is due mainly to the fabric-foam and ignition crib-sofa frame design interaction, which has been discussed earlier. Suffice it to say these particular full-scale furniture specimens do not reach a prolonged self-propagating combustion reaction.

8.3.3.1 Peak heat release rate

This comparison is shown below in **fig 8.70**. Both the CSIRO and University of Canterbury (UC) predictions based on their respective cone tests give very similar results, but significantly under predicted to those actually measured.

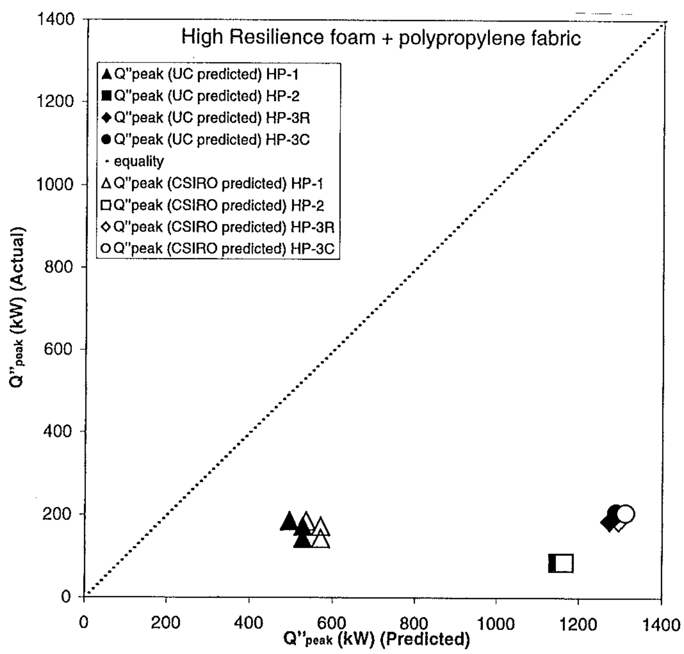

Figure 8.70 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) peak HRR. This is for the *High Resilience Polyurethane* foam + polypropylene fabric.

8.3.3.2 Time to reach peak heat release rate

The UC results give a relatively close comparison to those actually measured in the Furniture Calorimeter for the single seaters. The rest are all over predicted, which is conservative. Results are shown overleaf in **fig 8.71**.

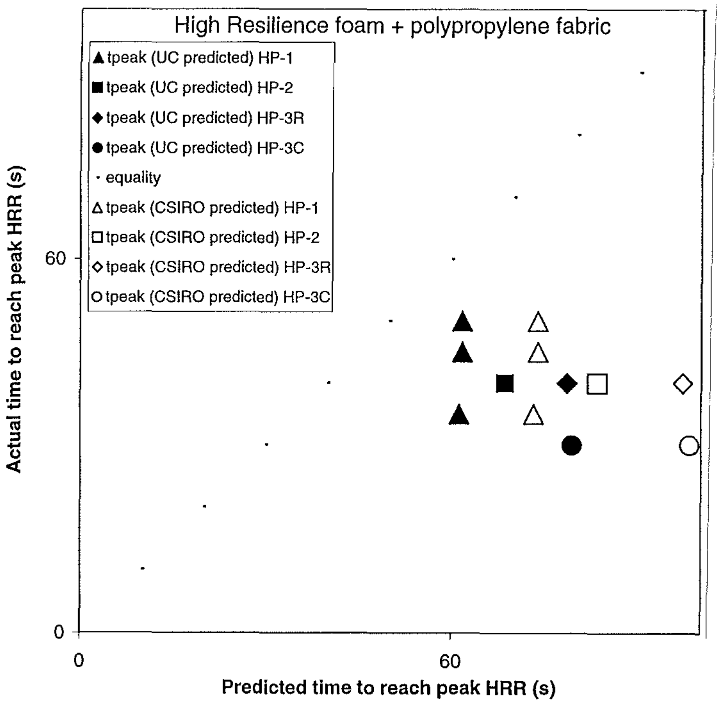

Figure 8.71 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) time to reach peak HRR (this time criterion starts once the HRR has exceeded 50 kW).. This is for the *High Resilience Polyurethane* foam + polypropylene fabric.

8.3.3.3 Total heat released

The results as illustrated below in **fig 8.72** sum up the reality of these tests – they just didn't really burn! The actually measured values are well below those predicted. Although this means that *CBUF Model I* errs on the conservative side (and is thus, a safe predictor of hazard), the scale of these over predictions suggest that this model has difficulty in accurately predicting the full-scale results of furniture constructed in this style from this type of foam.

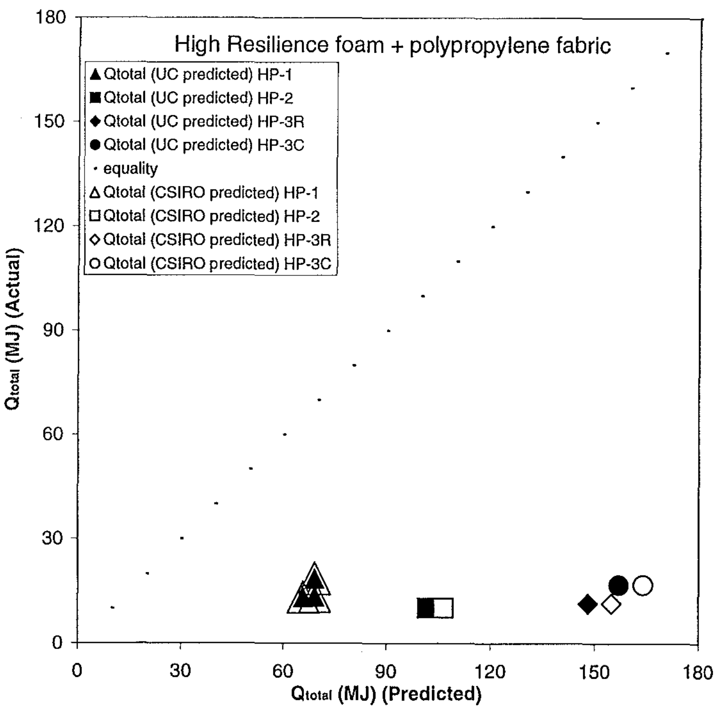

Figure 8.72 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) total heat released. This is for the *High Resilience Polyurethane* foam + polypropylene fabric.

8.3.4 High Resilience foam + cotton/linen fabric

The results for these correlations are shown in **figures 8.73 – 8.75**. This series gives good to average accuracy between the predicted versus measured fire parameters. The single and two seaters give the closest results. The three seaters are a little on the low side due to the fire resistance of the High Resilience foam in combination with the cotton/linen fabric reducing flame spread speed.

8.3.4.1 Peak heat release rate

This comparison is shown in **fig 8.73**. Both the CSIRO and University of Canterbury (UC) predictions based on their respective cone tests give very similar and comparable results to those actually measured for the single and two seater ranges. The three seaters are significantly over predicted and thus the predictions are conservative.

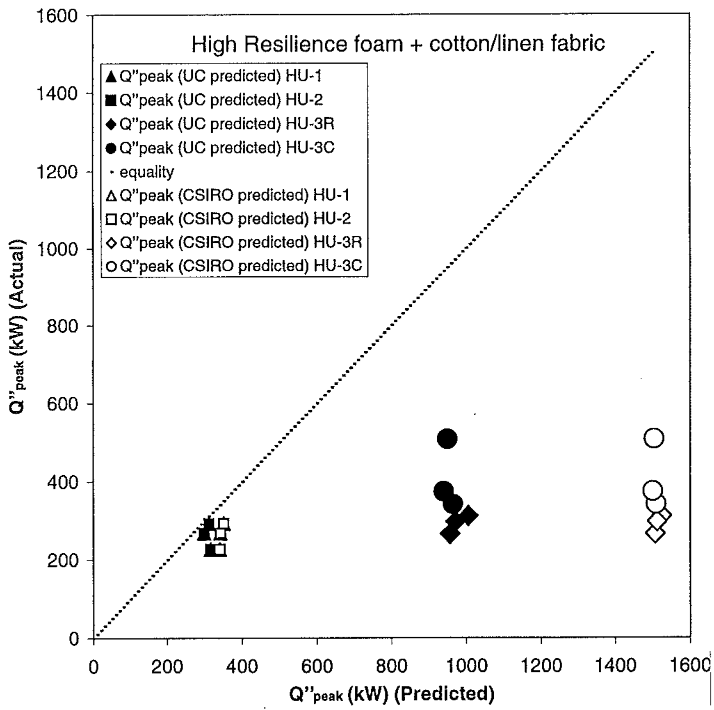

Figure 8.73 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) peak HRR. This is for the *High Resilience Polyurethane* foam + cotton/linen fabric.

8.3.4.2 Time to reach peak heat release rate

The UC results give a relatively close comparison to those actually measured in the Furniture Calorimeter for the single and two seaters. The three seaters are spread across the equatorial line, but generally over predicted. Results are shown below in **fig 8.74**. From video observations the flame spread determined by the characteristics of the cotton/linen fabric governed the speed of these tests.

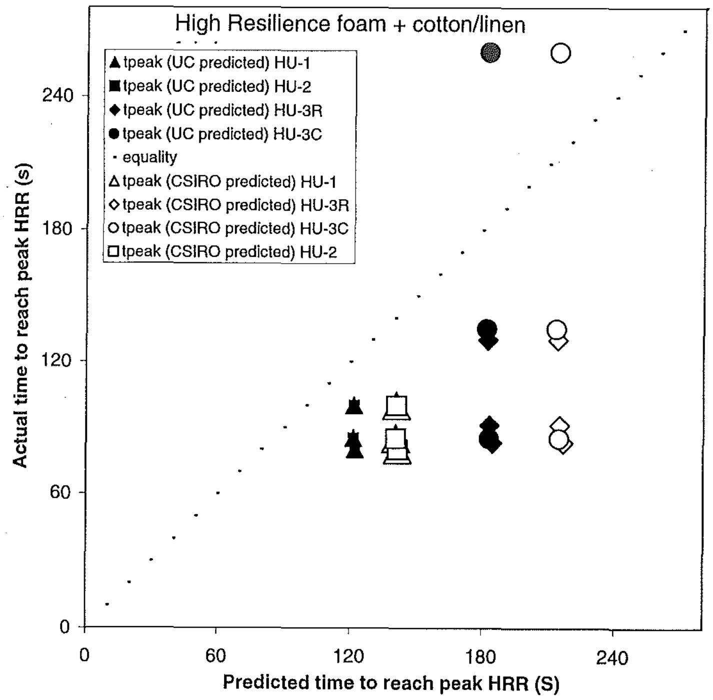

Figure 8.74 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) time to reach peak HRR (this time criterion starts once the HRR has exceeded 50 kW). This is for the *High Resilience Polyurethane* foam + cotton/linen fabric.

8.3.4.3 Total heat released

These results as illustrated below in **fig 8.75** give very close comparison to the measured values, although slightly over predicted (conservative). The right hand ignited three seaters displays slightly lower results, which is expected, from flame spread considerations. From observations of these tests, not all of the foam was consumed.

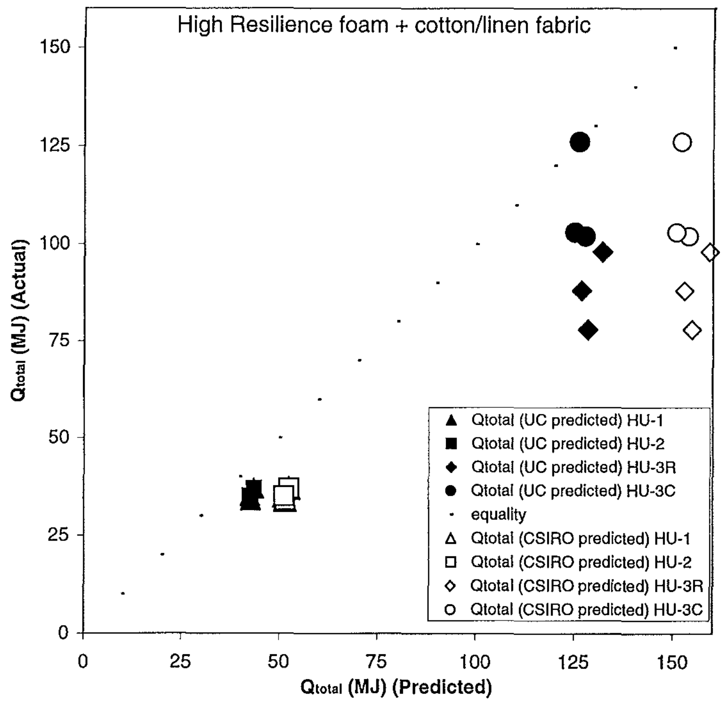

Figure 8.75 shows the predicted (based on the Cone Calorimetry tests conducted both at CSIRO and the University of Canterbury) vs the measured (CSIRO full-scale Furniture Calorimeter tests) total heat released. This is for the *High Resilience Polyurethane* foam + cotton/linen fabric.

8.3.5 Results based on CSIRO's Cone Calorimeter tests with edge frame

Because these tests were conducted on the High Resilience polyurethane foam + polypropylene fabric, which in the full-scale situation did not reach lasting, self-propagating combustion, it is not thought appropriate to compare these results. However, at lower heat flux irradiances the model, for this type of foam might provide closer predictions.

8.3.6 Partial correlating variable x_1

The predicted results are all obtained from statistically derived correlations. These correlations are based on the results obtained from characteristic HRR parameters obtained from representatively constructed Cone samples in the Cone Calorimeter and the combustible mass and style factor of the furniture specimen. However these correlating variables are chosen for applicability based on a preferential set of 'regimes'. These 'regimes' have been statistically derived so there are no 'first principles' upon which one regime can be proven to be a better fit than another. Because the ordering of these 'regimes' are dependent on the specimen sample size (total number of tests) for which the statistical conclusions have been formulated, it is useful to see which correlation variable and 'regime' best fits the data. The graph of this comparison is shown below in **fig 8.76**.

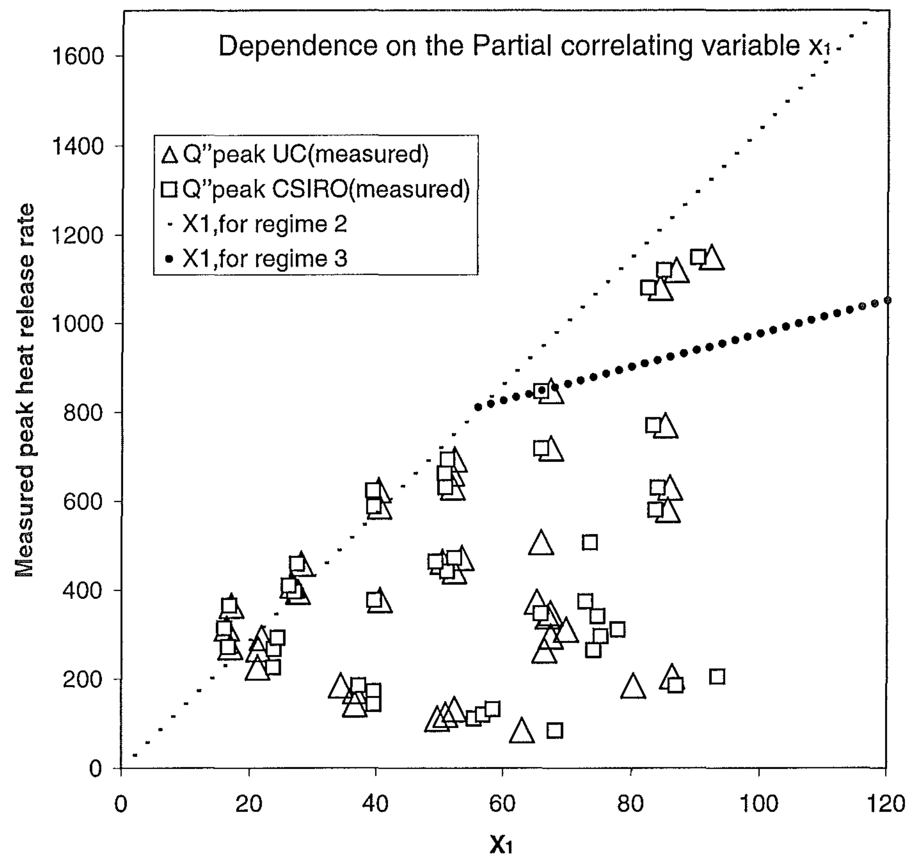

Figure 8.76 shows the partial dependence that the CSIRO furniture specimens display for the three different 'regimes' as defined in *Model I* of CBUF. For the triangles x_1 has been calculated using CSIRO's Cone Calorimeter results. The squares have used the University of Canterbury's results.

Although there are only two correlating variables (x_1 and x_2) and the three 'regimes' exist for distinct ranges these have been extended for x_1 on the graph to see the boundary conditions. For x_2 because it is only intended for the higher heat release rates it has been decided to retain its' earliest starting criterion at $x_1 > 40$ as stated in the CBUF report. (called 'regime 1'in this report).As can be seen the results at the lower HRR show a partial dependence upon x_1. But for the results at the higher HRR's none of the regimes appear to fit appropriately. This is thought to be due more to experimental characteristics inherent in the CSIRO furniture data, than a flaw in *Model I.*

It is quite possible that dilution effects (oxygen leaking into the line) or an overpowering of the exhaust gas duct system occurred at the higher HRR's, which would explain a general under measurement in HRR for the more severe furniture fires. All the measured values are close to or well under the predicted peak HRR, which is considered to be, in terms of life safety a very desirable result.

8.3.7 Uncertainty in results

The level of confidence of these results is dependent upon two factors. The first is the accuracy of the Cone Calorimeter tests upon which the predicted results are based on. The second is the level of accuracy of the Furniture Calorimeter tests against which the predicted results are compared. Unfortunately a detailed statistical analysis hasn't been able to be carried out to ascertain this confidence level.

8.3.7.1 Level of uncertainty in predicted results

The predicted results are based upon the Cone Calorimeter tests, conducted both at CSIRO and the University of Canterbury. It is important to know with what level of confidence these results can be stated. Unfortunately for this report it has not been possible to extend it to this level. However from **Table 7.1** and **7.2** the standard deviations and variations between each test have been calculated. These allow a first approximation as to the variation inherent in the raw data. As can be seen from **Table 7.1** (Cone results conducted by CSIRO) the *High Resilience Polyurethane* foam + cotton/linen fabric produce the most variation, with variations above 10% for almost all of the critical fire descriptors used in *Model I.* In **Table 7.2** (Cone results from the University of Canterbury), the corresponding percentage variations for the *High Resilience Polyurethane* foam + cotton/linen fabric are considerably less. However there are still some isolated high variations within these test results **Table 8.1** overleaf summarises the differences between the mean values for the CSIRO and University of Canterbury Cone Calorimeter results.

8.3.7.2 Level of uncertainty in measured results

Although it is known that no fire burns the same, it is possible, if correct and careful experimental procedure is followed to obtain very similar results. Many times the cost in both time and resources of maintaining these controls and exact procedures limits the number of tests that can be conducted. For a project of this scale (141 Furniture Calorimeter tests to be completed in nine and a half months), the experimental schedule required the testing of at least three specimens every day. Understandably this was a quite phenomenal undertaking when also considering that other projects when being done. The results obtained within each test series, foam + fabric combination shows quite good repeatability in the majority of the tests. Full size HRR curves for each test triplicate are shown in **Appendix K** to allow more accurate visual examination of the test details to be made.

Parameter	SP		SU		HP		HU	
	CSIRO	UC	CSIRO	UC	CSIRO	UC	CSIRO	UC
m (g)	20.2	**24.6**	18.0	**20.4**	25.9	**29.0**	23.3	**23.7**
t_{ig} (s)	6.0	**9.3**	6.0	**11.3**	6.0	**12.0**	6.0	**11.7**
q'' (MJm^{-2})	64.5	**64.4**	37	**35.9**	74.7	**74.3**	49	**39**
q''_{60} (MJm^{-2})	272	**336**	146	**255**	186	**285**	109	**150**
q''_{120} (MJm^{-2})	355	**384**	137	**194**	298	**379**	94	**150**
q''_{180} (MJm^{-2})	335	**348**	142	**158**	317	**390**	113	**160**
q''_{300} (MJm^{-2})	209	**288**	117	**142**	244	**257**	137	**132**
$t_{peak\ 1}$ (s)	80	**53**	15	**16**	100	**74**	18	**11**
$q''_{peak\ 1}$ (MJm^{-2})	464	**517**	255	**357**	462	**555**	248	**286**
t_{trough} (s)	123	**93**	107	**34**	162	**102**	68	**76**
q''_{trough} (MJm^{-2})	393	**390**	116	**257**	330	**442**	66	**113**
$t_{peak\ 2}$ (s)	135	**127**	165	**47**	192	**130**	205	**129**
$q''_{peak\ 2}$ (MJm^{-2})	389	**469**	161	**292**	375	**516**	248	**209**
$\Delta h_{c,eff}$ ($MJkg^{-1}$)	32	**26.1**	20.9	**19.9**	28.9	**27.7**	23.1	**19.2**

Table 8.1 compares the differences between the mean values of the CSIRO and University of Canterbury (UC) Cone Calorimeter results. SP = Standard Polyurethane foam + polypropylene fabric. SU = Standard Polyurethane foam + cotton/linen fabric. HP = High Resilience Polyurethane foam + polypropylene fabric. HU = High Resilience Polyurethane foam + cotton/linen fabric.

8.3.8 Discussion Summary

The furniture specimens when burnt in the Furniture Calorimeter displayed, at times widely-varying flammability behaviour, (thought most likely due to ignition characteristics). However when HRR curves were aligned around the 50kW level, within each test triplicate, reproducibility was generally quite good. And what one would expect, based on the comparative tests on the same fabric + foam combination in the other sofa seater arrangements.

The fabric/foam interaction was crucial in determining both whether the combustion reaction would become self-propagating (a measure of flame spread) and the degree of fire severity achieved (peak heat release rate).

The worst fabric/foam combination was undoubtably the *Standard Polyurethane* + polypropylene, which produced very high heat release rates, across all the seat ranges.

The ignition crib, although characterised, introduced increased complexity into the early stages of the furniture fire tests, and although an extremely important parameter to study, should really be left for examination later down the testing track. For this reason prediction measurements for the full-scale furniture specimens were compared with results recorded after it had exceeded 50kW.

CBUF Model I predicts quite accurately the *Standard Polyurethane* foam + fabric furniture specimens. The *High Resilience Polyurethane* foam it quite significantly over-predicted. Although this is always desirable in a model predicting hazard, it suggests that this model is not capable of accurately predicting the full-scale results of this combustion modified foam for this type of furniture style and thus might need to be modified to accommodate this type of foam.

Flame spread issues arose when comparing the chairs of the different series. Centre ignited specimens achieved results much closer to those predicted by the CBUF model. The right ignited seat cushions in the two and three seater range, were reduced in peak HRR and lagged behind in the time it took to reach this level. This was to be expected, and gives a good check against the other tests.

The denser the foam the better its' fire performance. Although the exact nature of the fire retardant additives in the three combustion modified *Polyurethane* foams (*High Resilience, Enduro & NOLITE*) was unknown, their fire performance increased as the density of these three foams increased respectively.

Although of undetermined significance in this series of tests, as no control was used, it is thought that the construction of the cushion covers played a part in the general, as observed, less than expected fire severity of the furniture's combustion behaviour. The overlapping, free ends of the fabric covers were only stapled together, resulting in little to no tensile stress on the fabric. It is a well-known fact that over stretched or tight covers, more quickly split, exposing the foam beneath, when exposed to a direct fire or heat attack.

The University of Canterbury's Cone Calorimeter tests show marked departure in three out of the four foam/fabric combinations, from the same, but slightly differently constructed series conducted on CSIRO's Cone Calorimeter, seven years prior. These differences were initially thought to have arisen from age degradation of the materials, but were higher than expected. It is thought that these differences are due almost exclusively to the differences in sample construction.

9 CONCLUSIONS

This research project has achieved several outcomes.

It has verified *Model I* of the CBUF report for the Standard Polyurethane foam + fabric combinations, with generally very close comparative values between the predicted versus measured results.

It has highlighted the importance of investigating the interaction between the fabric and foam, with the fabric displaying quite dominant effects in either reducing the peak HRR as for the cotton/linen fabric or enhancing the peak HRR as for the polypropylene fabric.

The demonstrated fire performance superiority of the *High Resilience Polyurethane* over *the Standard Polyurethane* foam has been confirmed. But further work is required to verify the most appropriate fabric covering.

Cotton/linen fabric proved far superior to polypropylene fabric in protecting the underlying foam for longer. This had the effect of delaying the onset of ignition (from video observations), reducing the peak HRR and increasing the time to reach peak heat release rate. All of these factors are desirable in reducing a fire hazard. The cotton/linen fabric does however, prolong the burning duration stage of the fire, although at a much reduced level of HRR.

The University of Canterbury's predictions for the burning behaviour of the full-scale specimens based on their cone tests were slightly closer in the majority of comparisons to the actual measured values than those conducted at CSIRO. This suggests that although cone sample construction was important it did not impact in this situation as significantly as at first thought. Of interest is that the predictions based on CSIRO's cone test results were almost consistently on the slightly more over-predicted side than those attributed to the University of Canterbury. This means CSIRO's cone samples were better fire performers. This is thought to be due to the construction differences.

10 FURTHER WORK

This work has great potential for extension. The following is a list of the areas that can be extended:

1. Comparison of the predicted full-scale results based on the CSIRO cone tests conducted at the 25 kWm^{-2} heat flux. This is a relatively easy analysis and would verify the most appropriate heat flux to be used with the CBUF *Model I* correlations.

2. The series of cushion arrangements could be expanded to include two and three seater sofas with armrests, ignited by cribs placed against an armrest and back cushion. Possible configurations are 20EA, 02EA, 22EA, 30EA, 03EA and 33EA.

3. A detailed study into the ignition characteristics of the furniture specimens and how the location of the ignition crib impacts on its burning behaviour. This could be used to design safer sofas. (For example the avoiding of cigarette traps; reduction of direct radiation surfaces; elimination of sharp furniture concave joins; use of char forming fabric; a standard for the stretching of fabric over furniture, to eliminate over tight fabric and thus weakening its fire resistance.

4. Derivation of (if possible) a simple formula for determining how geometry of cushions and ignition source impact upon the flame spread, HRR and burning behaviour of this sofa mock-up. (Primarily due to increased radiation from burning cushions). Confirmation that vertically positioned combustibles have a higher HRR than the same combustibles in a horizontal orientation.

5. An extension into the investigation of how fabric influences the fire behaviour of upholstered furniture. Lacking from the research data were full-scale tests of the foam just by itself. As was seen from the cone sample tests, the fabric played an important role, not just in prolonging the combustion reaction, but causing up to an 80% increase in the HRR.

6. A detailed investigation into the fabric – foam interaction, under the influence of fire. As seen from this data, the fabric impacted quite differently for different foams.

(a) An extension of this is then to combine it with how the furniture frame impacts upon this behaviour. From this investigation safer fire designed furniture frames (drains for melting foam etc.) and better foam – fabric combinations can be adopted.

7. Measurement of flame spread across the back and seat cushions, separately and when combined as a sofa. This is an important fire dynamic to understand and be able to predict, as flame spread is a major fire hazard criterion. There are already excellent video records of each specimen test to support this study.

8. An examination of the radiative component that is absorbed by the specimen when burning. Comparisons could be made between the individual back and seat cushion specimens and the superposition of them. How does this compare with the sofa specimen that contains both seat and back cushions? Questions to be answered would include a detailed fire dynamical description of how a simple upholstered chair burns.

9. The significance of the uncertainty inherent in the Cone Calorimeter results needs detailed analysis to determine how it propagates through the CBUF Model I. The resulting uncertainty should be reported with all future results so that the confidence level associated with any prediction can be determined.

10. CBUF Model II should be applied to this data, for the purposes of verification.

11. The behaviour of the specimen under separate ventilation and radiation conditions.
    (a) Free burn – well ventilated, little radiation return. As in the series conducted as described in this report.
    (b) Room burn – limited ventilation, re-radiation from the walls and ceiling. For the room burns the tests should be conducted in an ASTM standard room with dimensions 3660 x 2440 x 2440mm.

    The purpose of this would be to predict from the free burning tests what hazard would be expected in a standard compartment due to the burning specimen. It is expected that calculations can be made from the Cone Calorimeter specimen results to predict the full-scale free burn results. Thus from the bench-scale cone results the real life full-scale hazards could be determined.

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APPENDIX A

Calibration procedure for Furniture Calorimeter

Prior to the commencement of any tests a calibration is run each day. This is necessary to ensure that the readings obtained by the gas analysers are correct and that all other instructmentation is running correctly. To calibrate the gas analysers a 50-50 butane-propane fuel mixture is run through a gas burner under the Furniture Calorimeter collection hood for 10 minutes. This fuel is volumetrically metered to give a 300kW-heat release rate output. CSIRO's commissioning company regularly tests the accuracy of the volumetric metering of the fuel.

During the 10-minute test, the heat release rate history is calculated by the gas analysers via the oxygen consumption principle and then graphically displayed along with the actual 300kW-heat release rate curve that the metered gas supplies. **Fig A1** below shows a typical calibration curve along with the calculated heat release rate. If the values of the two curves are within 5% of each other then the Furniture Calorimeter is considered adequately calibrated.

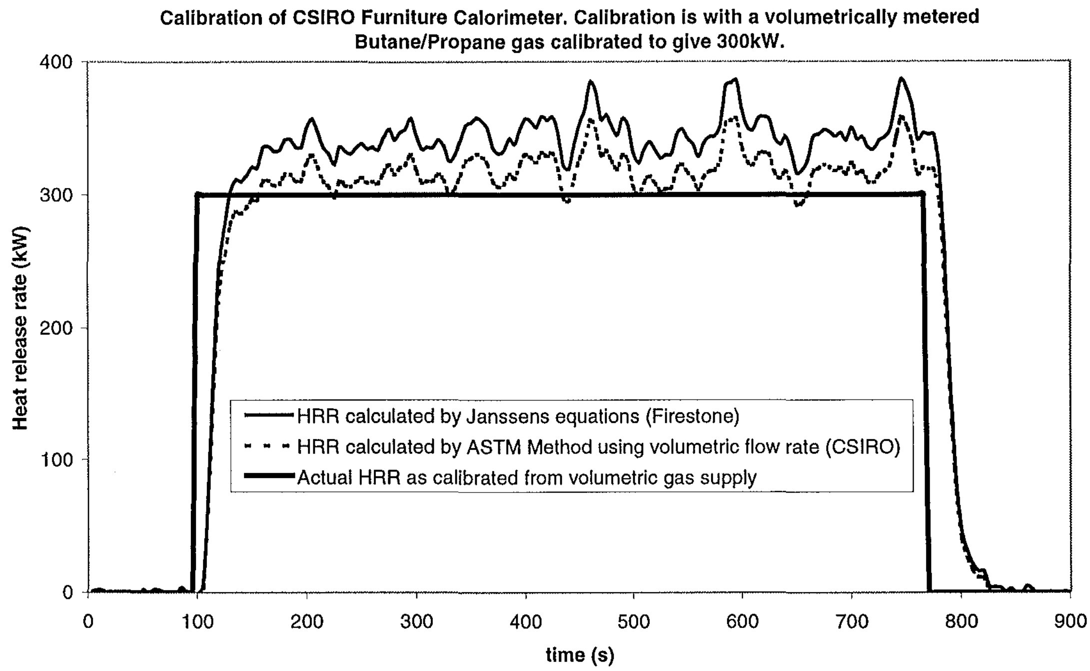


Figure A 1 shows the graphical display of the Furniture Calorimeter Calibration HRR

It is not clear why my calculations using Janssens equations are higher than the 300kW calibrated gas burner. Note the time delay for the gas analysers in the rising and falling edges of the calibration curve. This delay is 35seconds and is within that accepted by the standard. ISO 9705:1993, is the standard currently being used for calculation of the heat release from the Furniture Calorimeter. However for the tests in this report the standard used was the

ASTM draft method:ASTM (1983) Proposed method for room fire test of wall and ceiling materials and assemblies.

APPENDIX B

Measurement of air flow in the Furniture Calorimeter exhaust duct

For fully developed turbulent flow in the exhaust duct it is necessary to take measurements at least 25 to 40 pipe diameters, depending on the Reynolds number of the flow, downstream from the exhaust inlet, (Schlicting 1976). (For the CSIRO Furniture Calorimeter, measurements are taken at approximately 18 pipe diameters from the inlet, this translates into a time lag delay for the gas analysers of 35 seconds). As this distance makes the delay lag times too great for making practical gas analysis measurements, it is necessary to develop a method for determining the velocity shape factor, for non-fully developed flow. To do this it is necessary to make a series of differential pressure measurements across the cross section of the exhaust duct. From this the value and profile of the velocity shape factor can be determined.

For this calibration the differential pressure and temperature were measured at ambient conditions at four separate points along the cross section of the exhaust duct. This was repeated for varying exhaust duct extraction rates, of 10% intervals and is shown in table B1 below. It is safely assumed that the effect of a transient Reynolds number in non-fully developed fully is negligible. If high accuracy is not required, even fewer measuring points can be used. Winternitz and Fischl give the following formula as an alternate to the log-linear formula for calculating the mean velocity v_m from three measurements per exhaust duct diameter.

$$v_m = \frac{1}{5}\left[v_{0.500} + 2\left(v_{0.081} + v_{0.919}\right)\right],$$

where $v_{0.081}$, etc., represent the velocities at distances of 0.081, 0.500 and 0.919 pipe diameters from one wall.

Table B.1 overleaf shows the temperature and pressure measurements conducted within the duct for the purposes of calculating and characterising the flow rate and velocity profile.

Area of duct open	Position in duct where measurement was taken									
	1		2		3		4		**Centre**	
	ΔP	Temp	ΔP	Temp	ΔP	Temp	ΔP	Temp	ΔP	Temp
	mmH_2O	°C	mmH_2O	°C	mmH_2O	°C	mmH_2O	°C	mmH_2O	°C
10%	4.2	16.0	7.9	16.0	7.5	16.0	4.3	16.0	7.6	16.0
20%	15.9	16.0	24.8	16.0	25.0	16.0	15.4	16.0	25.1	16.0
30%	26.4	16.0	40.5	16.0	40.9	16.0	26.4	16.0	42.0	16.0
40%	36.5	16.0	57.2	16.0	58.0	16.0	36.7	16.0	58.0	16.0
50%	41.2	16.0	67.5	16.0	65.7	16.0	40.9	16.0	67.9	16.0
60%	47.8	16.0	76.5	16.0	75.9	16.0	47.8	16.0	76.5	16.0
70%	52.3	16.0	78.8	16.0	78.5	16.0	52.2	16.0	78.9	16.0
80%	53.9	16.0	81.4	16.0	81.6	16.0	53.6	16.0	82.1	16.0
90%	54.1	16.0	84.9	16.0	84.2	16.0	54.4	16.0	84.7	16.0
100%	55.5	16.0	86.3	16.0	86.5	16.0	55.4	16.0	86.7	16.0

Table B 1 shows the pressure and temperature measurements obtained across the exhaust duct at varying duct extraction rates.

Where position	**1**	= 0.043D	(16mm from east wall of duct)
	2	= 0.290D	(110mm from east wall of duct)
	3	= 0.710D	(270mm from east wall of duct)
	4	= 0.957D	(364mm from east wall of duct)
	Centre	= centre of duct	(185mm from east wall of duct)

It is now possible to calculate k_t, which is defined as the ratio of the average mass flow per unit area to the centre line mass flow per unit area in the exhaust duct. Note the bi-directional probe is located in the centre of the duct during the furniture calorimeter tests.

Calculation of k_t

From the above description, in formula form k_t, is defined below,

$$k_t = \frac{Q_{average}}{Q_{centre}},$$

where Q is the flow rate and is defined as,

$$Q = A \times v$$

where A is the internal cross sectional area of the exhaust duct and v is the velocity of the exhaust gases.

$$v = k_p \sqrt{\frac{2\Delta P}{\rho}},$$

where k_p is the calibration constant of the bi directional probe (1.08), ΔP is the differential pressure and ρ is the density of the exhaust gases.

For the four measurements taken across the duct the average flow rate is,

$$Q_{average} = \frac{1}{4}\left(Q_1 + Q_2 + Q_3 + Q_4\right),$$

So k_t is written as,

$$k_t = \frac{\pi v^2 \left[\frac{k_p}{4}\left(\sqrt{\frac{2\Delta P_1}{\rho_1}} + \sqrt{\frac{2\Delta P_2}{\rho_2}} + \sqrt{\frac{2\Delta P_3}{\rho_3}} + \sqrt{\frac{2\Delta P_4}{\rho_4}}\right)\right]}{\pi v^2 k_p \left(\sqrt{\frac{2\Delta P_{centre}}{\rho_{centre}}}\right)}$$

But $\rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_{centre}$ as all measurements are taken at the same temperature (16 ^{0}C). Therefore k_t can be simplified to,

$$k_t = \frac{\sqrt{\Delta P_1} + \sqrt{\Delta P_2} + \sqrt{\Delta P_3} + \sqrt{\Delta P_4}}{4\sqrt{\Delta P_{centre}}}$$

The results are summarised in table B2 below.

Area of duct open	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
k_t	0.88	0.89	0.89	0.90	0.88	0.89	0.91	0.90	0.90	0.90

Table B 2 shows the calculated values of k_t for the varying duct extraction rates. The data for this calculation was obtained from Table B1.

The average value for k_t is therefore **0.89.**

APPENDIX C

Protocol for the CSIRO furniture ignition crib

Assessment of the fire behaviour of furniture is complex, not just because of the very many types and styles, material and foam combinations and categories of use, but also the variety and variation of attack of ignition sources. It is also important that for a standardised ignition source to be adopted it must have sufficient flaming and sustained ignition to represent the majority of likely sources of attack. Other criteria are that it must have good repeatability and reproducibility.

Past ignition sources such as crumpled newspaper (Moulen & Grubits 1981) was found to burn in an erratic and unpredictable manner. Small cross piles of wood sticks as specified in DD58 (British Standards Institution 1978) as ignition sources 4, 5, 6 and 7 were did not always burn evenly or to completion, often toppling over and spreading their embers in a random pattern. Although these methods had been proposed, CSIRO felt that they lacked the required prerequisites.

It was for this reason that CSIRO developed the wood ignition crib series, which cover the majority of ignition source needs of standard fire tests. Considerable work has been done to demonstrate that these cribs burn in a repeatable and reproducible manner, providing a series of well-graded burning characteristics. Reproducible burning of the cribs is facilitated by igniting it, with a gas flame in quick succession, at the bottom centre of the three exposed sides. The remaining side being placed against the back of the item to be tested (chair).

The ignition crib is constructed as a cross pile of timber (*Pinus radiata*) sticks of density 500 kgm^{-3}, (being essentially knot free wood), with dimensions not exceeding 150 x 50 x 1000mm. They are cut with a fine-tooth circular saw and are conditioned for a minimum of 7 days at 20°C and 65% RH, prior to being used. The stick width is chosen based on type of ignition source being modelled. The number of sticks required for a crib is controlled strictly by mass, but will be in the range of between 100 – 130 sticks. This varies due to the different masses of the cribs. When constructing the crib the sticks are staggered as shown in **Fig C1** for the 50g crib.

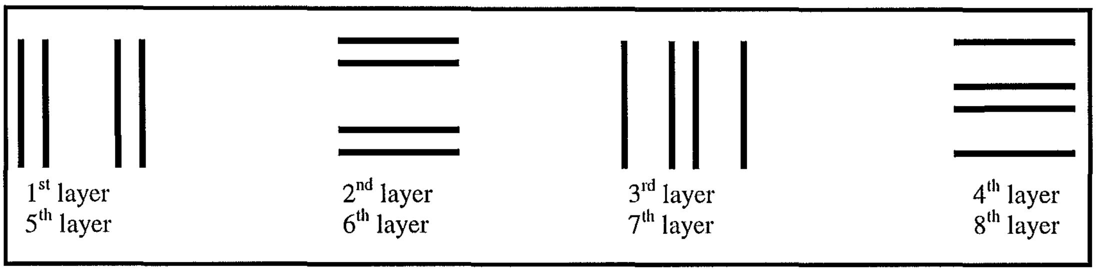


Figure C 1 shows the staggered layer arrangement for the 50g-ignition crib.

The crib is constructed *in situ* by building cross-piles of evenly spaced sticks, using the number of sticks per layer as specified below in **Table C1**.

Crib mass (g)	Stick width (mm)	Stick length (mm)	# of sticks per layer
50$\pm$0.5	2.0$\pm$0.2	200$\pm$1	4
100$\pm$1.0	3.0$\pm$0.2	200$\pm$1	5
150$\pm$1.5	3.5$\pm$0.2	200$\pm$1	7
200$\pm$2.0	4.0$\pm$0.2	200$\pm$1	8
300$\pm$3.0	5.0$\pm$0.2	200$\pm$1	10
400$\pm$4.0	6.0$\pm$0.2	200$\pm$1	11

Table C 1 shows the details and tolerances of the wood sticks for the ignition cribs.

APPENDIX D

Furniture Calorimeter tests – description and control list

CSIRO conducted 141 Furniture Calorimeter tests on chair specimens. These were labelled alphanumerically in the corresponding order according to:

- **Number of back cushions** — Specimens contained between 1 to 3 back cushions, and were labelled according to their number. eg. **1**, **2** or **3**.
- **Number of seat cushions** — Specimens contained between 1 to 3 seat cushions and were labelled according to their number. eg. **1**, **2** or **3**.
- **Location of ignition crib** — Ignition crib placement either on the centre of the central seat cushion, centre of the right most seat cushion or on the right of the right most seat cushion. This was denoted by either **C**, **R** or **E** respectively.
- **Existence of armrest** — If the specimen contained armrests it was labelled with an **A**.
- **Cushion padding** — Four different types of foam were used, they were all from the *Dunlop/Olympic* range.
  - **S** denotes *Dunlop/Olympic*A23 – 130
  - **H** denotes *Dunlop/Olympic*HR32 - 80
  - **M** denotes *Dunlop/Olympic* END 36 – 100 CM
  - **N** denotes *Dunlop/Olympic* NLB 45 - 130
- **Fabric cover** — Two types were used,
  - **U** denotes Cotton/Linen Union, whilst
  - **P** denotes Polypropylene.
- **Sequence of test** — Each Furniture Calorimeter test was given a number code according to the order that it was tested. eg. **FC45**, stands for Furniture Calorimeter test 45. Each test series was conducted in triplicate to determine repeatability and reproducibility.

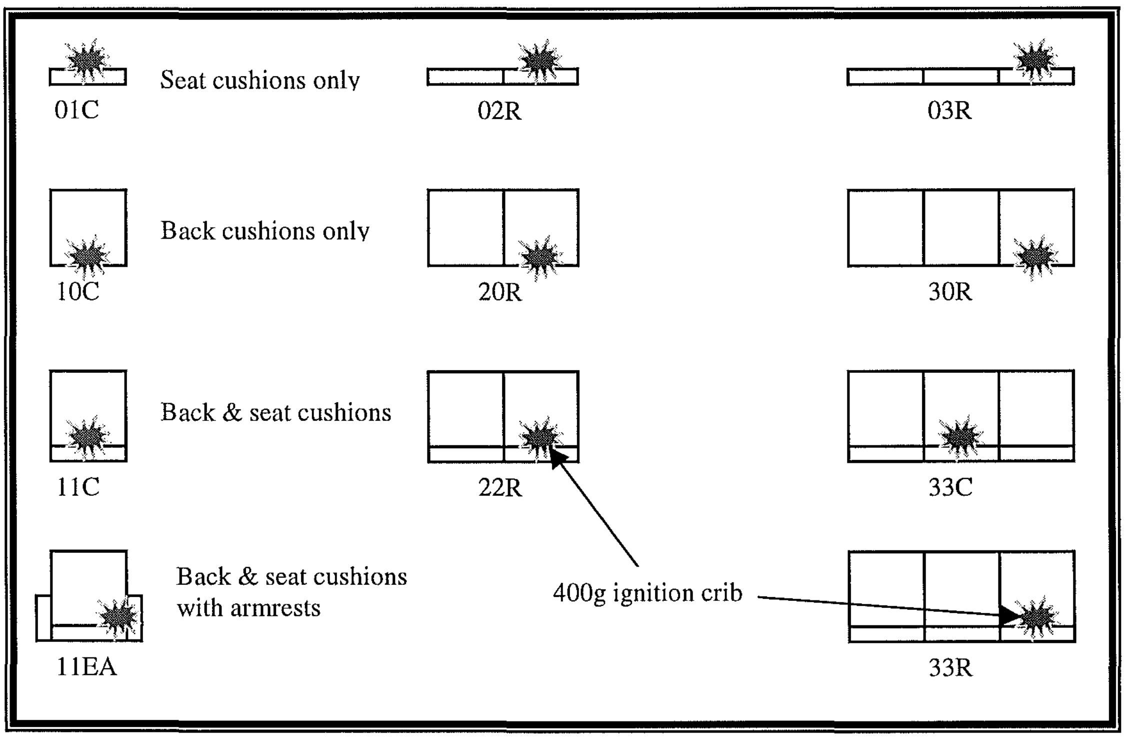


Figure D 1 shows diagrammatically the cushion arrangements with their alphanumeric codes.

Furniture Calorimeter sofa burn series - control list

The following table shows the test specimens and their code descriptor. The specimens that were only seat or back cushions had concrete fibreboard panel in place of the absent cushions to simulate the same ventilation conditions.

Specimen description			Alphanumeric code of specimen	Furniture Calorimeter test 1	2	3	4
	Single seater specimens	Seat cushion	01C SU	FC79	FC80	FC81	
			01C SP	FC82	FC83	FC84	
			01C HU	FC85	FC86	FC87	
			01C HP	FC88	FC89	FC90	
		Back cushion	10C SU	FC91	FC92	FC93	
			10C SP	FC94	FC95	FC96	
			10C HU	FC97	FC98	FC99	
			10C HP	FC100	FC101	FC102	
		Sofa	11C SU	FC65	FC67	FC69	
			11C SP	FC66	FC68	FC70	
			11C HU	FC71	FC72	FC73	FC74
			11C HP	FC75	FC76	FC77	FC78
			11C MU	FC151	FC153	FC154	
			11C MP	FC152	FC155	FC156	
			11C NU	FC148	FC149	FC150	
			11C NP	FC145	FC146	FC147	
	Two seater specimens	Seat cushion	02R SU	FC40	FC41	FC43	FC45
			02R SP	FC42	FC44	FC46	
			02R HU	FC47	FC50	FC52	
			02R HP	FC48	FC49	FC51	
		Back cushion	20R SU	FC53	FC54	FC57	
			20R SP	FC55	FC56	FC58	
			20R HU	FC59	FC61	FC63	
			20R HP	FC60	FC62	FC64	
		Sofa	22R SU	FC29	FC30	FC32	
			22R SP	FC28	FC31	FC33	
			22R HU	FC34	FC37	FC38	
			22R HP	FC35	FC36	FC39	
	Three seater specimens	Seat cushion	03R SU	FC103	FC104	FC105	
			03R SP	FC106	FC107	FC108	
			03R HU	FC109	FC110	FC111	
			03R HP	FC112	FC113	FC114	
		Back cushion	30R SU	FC115	FC116	FC117	
			30R SP	FC118	FC119	FC120	FC121
			30R HU	FC122	FC123	FC124	
			30R HP				
		Sofa	33R SU	FC125	FC126	FC127	
			33R SP	FC128	FC129	FC130	
			33R HU	FC131	FC132	FC133	
			33R HP	FC134			
		Sofa	33C SU	FC136	FC137	FC138	
			33C SP	FC139	FC140	FC141	
			33C HU	FC142	FC143	FC144	
			33C HP	FC135			
	Chair with armrest		11EA SU	FC163	FC164	FC165	
			11EA SP	FC166	FC167	FC168	
			11EA HU	FC160	FC161	FC162	
			11EA HP	FC157	FC158	FC159	

Table D 1 Shows the test specimens and their descriptor codes

Nordtest sofa frame

All of the furniture specimens were tested on the same sofa frame that conformed to the standard as stated in the Nordtest. It was constructed from 2 centimetre square steel, thick walled hollow tube and is shown in **fig D2** below.

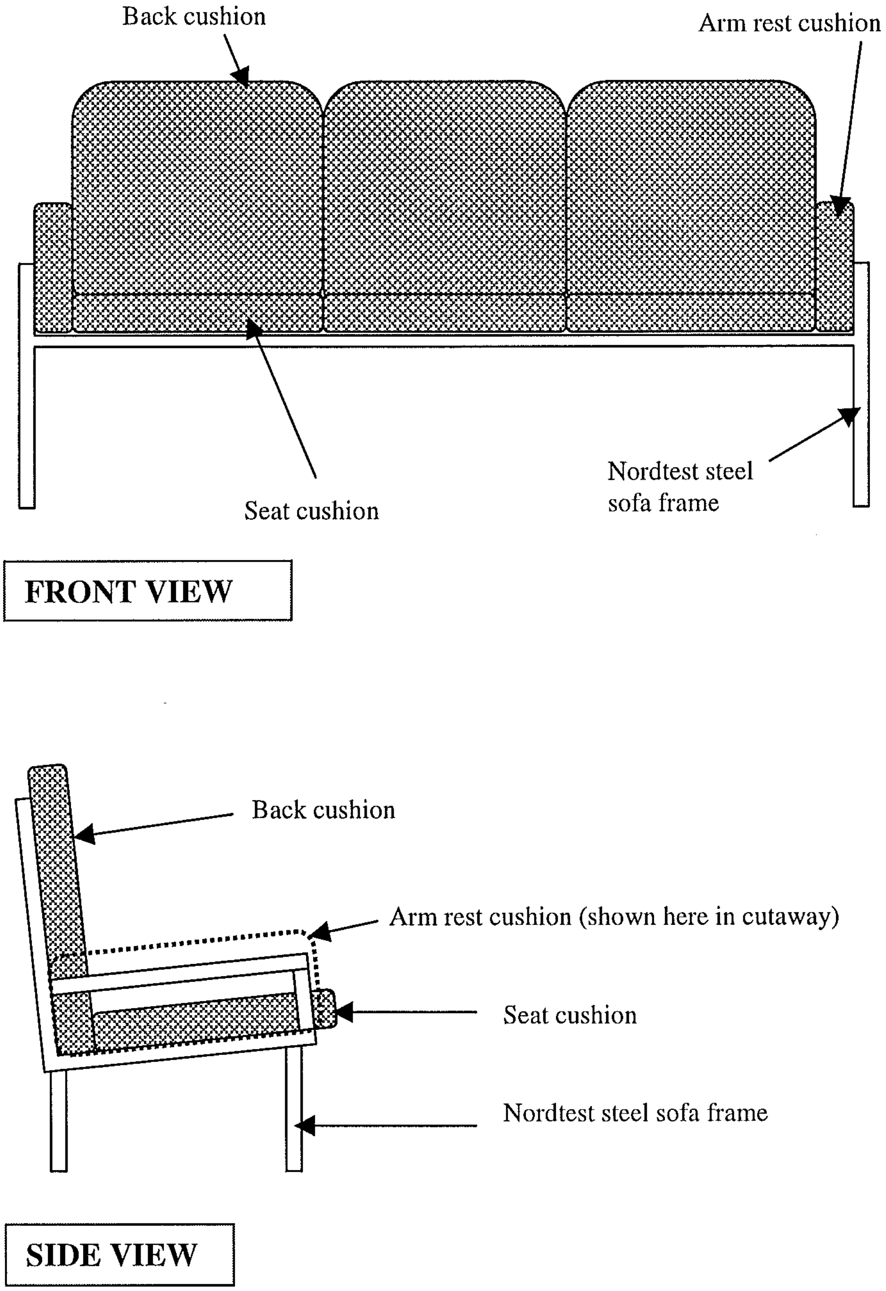


Figure D 2 shows the Nordtest sofa frame used for the furniture burns.

APPENDIX E

Furniture calorimeter test record for furniture specimens

The details of each test specimen, including construction components and weights, ambient test conditions and burn duration is shown below in **Table E1**.

Specimen code	Test	Construction: Foam	Construction: Fabric	Weight: Foam (kg)	Weight: Fabric (kg)	Test conditions: Temperature (°C)	Test conditions: Humidity (%)	Test conditions: Pressure (mmbar)	Burn duration (s)
11C SU	FC65	Standard	Cotton/Linen	1.51	0.38	14	89	1026	480
	FC67			1.53	0.38	16	84	1026	538
	FC69			1.48	0.36	17	82	1026	482
11C SP	FC66		Polypropylene	1.49	0.51	15	88	1026	
	FC68			1.43	0.52	16.5	83	1026	
	FC70			1.51	0.52	17	81	1026	
11C HU	FC71	High Resilience	Cotton/Linen	2.1	0.37	15	73	1020	
	FC72			2.15	0.37	15	62	1019	
	FC73			2.09	0.37	15	70	1019	
	FC74			2.02	0.35	15	75	1017	
11C HP	FC75		Polypropylene	2.13	0.52	10	83	1028	
	FC76			2.14	0.51	11	83	1028	
	FC77			2.03	0.49	11	84	1029	
	FC78			2.15	0.50	12	82	1028	
22R SU	FC29	Standard	Cotton/Linen	3.03	0.75	27	61	1016	
	FC30			3.01	0.79	21	81	1019	
	FC32			2.92	0.77	23	76	1019	
22R SP	FC28		Polypropylene	3.03	1.06	24	72	1014	350
	FC31			3.03	1.06	22	80	1020	
	FC33			2.99	1.10	21	72	1024	
22R HU	FC34	High Resilience	Cotton/Linen	4.12	0.75	22	71	1024	
	FC37			4.22	0.75	18	73	1019	
	FC38			4.32	0.76	18	72	1019	
22R HP	FC35		Polypropylene	4.25	1.08	21	64	1023	
	FC36			4.29	1.04	20	64	1023	
	FC39			4.17	1.04	20	69	1019	
33C SU	FC136	Standard	Cotton/Linen	4.38	1.19	16	82	1021	
	FC137			4.44	1.09	18	74	1021	
	FC138			4.47	1.07	21	70	1020	
33C SP	FC139		Polypropylene	4.83	1.46	24	66	1019	
	FC140			4.52	1.47	26	61	1017	
	FC141			4.38	1.47	28	56	1016	362
33C HU	FC142	High Resilience	Cotton/Linen	6.20	1.10	22	68	1019	600
	FC143			6.30	1.09	23	69	1017	780
	FC144			6.17	1.07	24	66	1017	722
33C HP	FC135		Polypropylene	6.39	1.53	20	60	1023	1202
33R SU	FC125	Standard	Cotton/Linen	4.45	1.12	25	81	1007	
	FC126			4.33	1.08	27	70	1006	720
	FC127			4.57	1.10	27	69	1007	
33R SP	FC128		Polypropylene	4.45	1.49	20	80	1010	
	FC129			4.42	1.50	19	84	1010	
	FC130			4.40	1.50	19	62	1025	
33R HU	FC131	High Resilience	Cotton/Linen	6.26	1.08	20	60	1023	
	FC132			6.44	1.20	20	60	1024	
	FC133			6.34	1.09	16	61	1023	
33R HP	FC134		Polypropylene	6.26	1.49	18	69	1023	

Table E 1 shows the specimen details and ambient conditions during each test.

APPENDIX F

CSIRO cone sample test details

Each particular fabric/foam combination was tested in triplicate at an irradiance of 25 and 35kWm^{-2}. As there were two different types of foam and fabric this made a test sample size of 24. Each test was prescribed a code for reference. The tests ending in either an A, B or C were all tested on 19th January 1993, while the tests ending in either a D, E or F were all tested on the 17th February 1993. The only exception to this was test PU&C39A, which was tested on the 17th of February 1993. All the tests conducted in January had Cone Calorimeter gas analyser delay times of 14, 11 and 12 seconds for O_2, CO and CO_2 respectfully. The later tests had delay times of 18, 11, and 12 seconds for O_2, CO and CO_2 respectfully, due to the re-routing of the oxygen analyser gas line. **Table F1** below shows the cone sample test data.

Sample code	Sample construction		Total mass (g)	Heat flux (kWm^{-2})	Ignition time (s)
	Foam	Fabric			
PU&C36A	Standard Polyurethane	100% Polypropylene	19.8	35	6
PU&C36B			20.2		6
PU&C36C			20.6		6
PU&C36D			20.2	25	8
PU&C36E			20.3		7
PU&C36F			20.0		9
PU&C37A	High Resilience		24.6	35	6
PU&C37B			27.2		6
PU&C37C			26.0		6
PU&C37D			26.8	25	10
PU&C37E			26.3		9
PU&C37F			26.7		9
PU&C38A	Standard Polyurethane	Cotton/ Linen Union	18.1	35	6
PU&C38B			17.6		6
PU&C38C			18.0		6
PU&C38D			18.7	25	12
PU&C38E			19.3		10
PU&C38F			17.0		10
PU&C39A	High Resilience		23.6	35	6
PU&C39B			23.8		6
PU&C39C			22.4		6
PU&C39D			24.3	25	12
PU&C39E			21.8		12
PU&C39F			22.8		11

Table F 1 shows the cone sample test data.

On 17th December 1998 a further series of tests were conducted on one fabric/foam combination (polypropylene fabric/High Resilience foam). Three cone heat flux irradiances (15, 25 & 35kWm^{-2}) were used each tested in triplicate, making a sample size of nine. The gas analysers had the same delay times as the 17th February 1993 tests. An edge frame was used around all samples. **Table F2** below summarises the details for these tests.

Test code	Sample weight (g)		Sample test time (s)			Heat flux (kWm^{-2})	Observations
	Foam	Total	Ignition	Flame out	Burn time		
FP17515 A	16.9	29.0	27	325	298	15	
FP17515 B	16.8	28.7	26	325	299		
FP17515 C	16.8	28.7	29	390	361		
FP17525 A	16.6	28.5	14	330	316	25	
FP17525 B	16.8	28.9	12	315	303		
FP17525 C	16.7	28.9	15	338	323		
FP17535 A	16.7	28.5	8	304	296	35	
FP17535 B	16.9	28.9	25	310	285		Spark igniter failed (spontaneous ignition)
FP17535 C	16.6	28.6	7	305	298		

Table F 2 shows details of cone tests conducted at CSIRO on 17th December 1998.

APPENDIX G

Canterbury University cone sample test details

On the 3rd February 1999 an additional series of tests were conducted with cone samples constructed from the original materials – this time to the CBUF protocol. Each particular fabric/foam combination was tested in triplicate at an irradiance of $35kWm^{-2}$. As there were two different types of foam and fabric this made a test sample size of 12, but as an additional measure the foam by itself was tested bringing the total number to 18. The samples were conditioned for 1-week prior to the test at $20^{0}C$ and 50% Relative Humidity. The ambient conditions in the laboratory on the day of the testing were:

Temperature	19 ^{0}C
Relative Humidity	67 %
Pressure	1013.5 kPa (assumed)

Table G1 below shows the cone sample test data. Only three from each series were used, the rest, being outliers were discarded.

Test code	Sample construction		Sample weight (g)			Sample test time (s)			Observations
	Foam	Fabric	Fabric	Foam	Total	Ignition	Flame out	Burn time	
S0_1	Standard Polyurethane	None	-	11.85	11.85	7	146	139	Foam quickly melted forming a pool in the bottom of foil
S0_2				11.85	11.85	6	135	129	
S0_3				11.86	11.86	6	143	137	
S0_4				11.95	11.95	4	160	156	
SP_1		Polypropylene	11.22	11.91	23.13	10	227	217	Fabric melted, exposing foam, which melted, forming a pool in bottom of foil. By tests end bottom of foil disintegrated
SP_2			11.12	11.93	23.05	9	235	226	
SP_3			11.33	11.89	23.22	9	230	221	
SC_1		Cotton/Linen	7.24	11.81	19.05	11	320	309	Fabric charred, but disintegrated approximately halfway through the test
SC_2			7.03	11.89	18.92	11	367	356	
SC_3			7.01	11.89	18.90	12	287	275	
HR0_1	High Resilience	None	-	16.79	16.79	3	183	180	Foam shrunk down prior to igniting
HR0_2				16.79	16.79	5	230	225	
HR0_3				16.79	16.79	3	172	169	
HR0_4				16.44	16.44	4	228	224	
HR0_5				16.43	16.43	4	170	166	
HR0_6				16.42	16.42	5	180	175	
HR0_7				16.50	16.50	46	192	148	Foam shrunk down by 2/3 prior to igniting
HRP_1		Polypropylene	11.04	16.58	27.62	36	319	283	Fabric very quickly melted exposing the foam, which shrunk down
HRP_2			11.09	16.58	27.67	11	237	226	
HRP_3			10.87	16.63	27.50	16	270	254	
HRP_4			10.95	16.62	27.57	9	227	218	
HRC_1		Cotton/Linen	7.04	16.68	23.72	13	501	488	Fabric badly charred, but remained almost completely intact for entire test
HRC_2			6.84	16.66	23.50	13	540	527	
HRC_3			6.88	16.65	23.53	12	498	486	
HRC_4			7.19	16.49	23.68	13	490	477	
HRC_5			7.10	16.70	23.80	12	450	438	

Table G 1 shows details of cone tests conducted at CSIRO on 17th December 1998.

APPENDIX H

Polyurethane foam

Flexible polyurethane foams became increasingly available, commercially about thirty years ago and since then their use has become widespread in many industries. They account for the largest share of upholstery filling materials and automotive seating; they are used in bedding and many apparel and footwear articles incorporate foam laminates. The industrial applications include thermal and acoustic insulation, packaging protection, filtration, loudspeaker grills, horticulture, and many other varied fields.
The high degree of acceptance which flexible polyurethane foams have gained in the areas of domestic comfort mean that a relatively large quantity is present in homes, caravans, hospitals, hotels and commercial premises. The annual consumption of flexible foam is equivalent to
Flexible polyurethane foam being an organic material belonging to the plastic's family, burns very fiercely in unprotected situations when exposed to fire. It has also been found that the lower the density of the plastic material the more prone to burning they become. Polyurethane foams are amongst the lowest density plastics found.

Summary data

Dunlop Flexible Foams manufactured all of the foam types used in these tests. They are one of the largest producers of polyurethane foam in Australasia and have an extensive product range. These foams all came from the *Dunlop-Olympic* product range. **Table H.1** below shows the properties of the foams that were used in this research. The *NOLITE* and *Enduro* foams were only tested in the single seaters.

Property	**Polyurethane foam**			
	Standard	*High Resilience*	*Enduro*	*NOLITE*
Colour	Pale grey	Pale blue	Pale yellow	Steel blue
Density	23	32	36	45
Hardness	130	80	100	130
IFD 25%			85 - 105	90 - 110
IFD 40%			110 - 140	115 - 145
IFD 65%			205 - 250	220 - 270
IFD 25% recovery			75% min	80% min
Indentation factor			2.39	2.45
Tensile strength			100kPa min	65kPa min
Elongation			150% min	125% min
Resilience			55% min	55% min
Compression set (75%)			8% max	15% max
Fire retardants	No fire retardant additives	Good fire performance	Top-class Combustion-modified foam	Superior fire performance
Uses	Conventional general purpose seating foam	Better quality seating foam, used more for back cushions	Quality furniture Public halls Transport seating	Public halls Transport seating Bedding

Table H 1 lists the properties of the foams used in this research

Properties of foam explained

Density
The mass per unit volume of foam measured in kgm^{-3}.

Hardness (IFD)
This is the force that is required to compress the foam by 25%, 40% and 60% of its initial thickness using a 200mm in diameter standard indentor. It is expressed and measured as indentation force deflection (IFD). The reference hardness is taken at the 40% indentation force deflection value.

IFD 25% Recovery
This is the measure of elasticity or hysteresis of a foam sample and is defined as the ratio of IFD forces on 25% deflection return (unloading) cycle to IFD 25% on loading. A high ratio of 25% recovery, of between 75 - 85% indicates good recovery properties.

Indentation Factor
This property is one of the indicators of foam comfort. Higher indentation or "sag" factor figures mean softer "initial feel" coupled with good base support. Generally this is in the range of between 1.6 - 2.6 for 50mm test pieces and is defined as the IFD at 65% divided by the IFD at 25%.

Resilience
This is measured as ball rebound, it is an indication of the bounciness of the material. Seating foams are generally in the range of between 40 - 60%. For more impact absorbing grades this reduces to less than 30%.

Tear resistance
This is a measure of the resistance of the foam to tearing.

Elongation
This is a measure of the percentage extension of the test piece at the point of maximum stretch, before breaking. Elongation is measured together with **Tensile strength**.

Tensile strength
The force required to stretch the foam until it reaches its break-point.

Compression set
This is measured by compressing a 25mm thick sample for 22 hours at $70^{0}C$ and measuring the percentage thickness lost following the compression cycle.

Flammability Standards
Many specialised foams must undergo standardised methods in which a test sample of the material, such as the foam or foam + fabric cover combination are subjected to ignition sources of varying intensity for a given time. Performance in such tests is graded, with the highest fire resistance rating given to the best performing foam.

APPENDIX I

Specifications for the *Datalogger* used in the Furniture Calorimeter

Datataker 505/605

DATA LOGGER

The Datataker 505 and 605 are microprocessor based, battery powered data loggers which measure inputs from most sensor types. Analog input channels are relay multiplexed, providing higher voltage measurement range, greater common mode range and tolerates larger withstanding voltages than Datataker 500 and 600.

Data manipulation includes statistical functions, calculations and sensor calibration. Data is stored in battery backed RAM and removable memory cards. Alarms can be set for all channels.

The Datataker 605 has an integral display and keypad.

Suitable for scientific, industrial and public utility applications.

Analog Inputs

- 10 differential or 30 single ended, can be used in any mix.
- Expansion by external modules with 10 differential or 30 single ended analog input channels. Maximum two modules supported.
- Autocalibrating and autoranging, 4 decades.
- Resolution 15 bit plus sign, 1µV.
- Sampling rate 25 samples/second.
- Accuracy better than 0.15% of full scale.
- Linearity better than 0.05%
- Input impedance 1MΩ, or >100MΩ selectable.
- Common mode range ±100VDC.
- Input withstanding voltages for analog channels
  - Unselected channels - ±1.5KVDC for 10µS
    - ±500VDC for 50mS
    - ±100VDC continuously
  - Selected channels - ±100VDC continuously
- Common mode rejection >90db, 110db typical.
- Series mode line rejection >35db
- Sensor excitation of 5V, 250.0µA or 2.500mA each channel.
- 4, 3 and 2 wire resistance, RTD and thermistor measurement.
- Full, half and quarter bridges, voltage or current excitation.
- Relay multiplexer.

Digital Inputs

- 4 TTL/CMOS compatible digital input channels for digital state, byte, events and low speed counters 10Hz, 16 bit, presettable.
- Digital inputs share with digital output channels.
- Expansion by external modules.
- 3 high speed counters, 1KHz normally, or 1MHz optionally, 16 bit, presettable.
- Analog channels also read digital state, user definable threshold.

Ranges

Input Type	Range	Units	Resolution
DC Voltage	±25.000	mV	1µV
	±250.00	mV	10µV
	±2500.0	mV	100µV
	±100.00	V	10mV
DC Current	±0.2500	mA	200nA
Internal Shunts	±2.500	mA	1µA
	±25.00	mA	10µA
External Shunts	Any range	mA	
4-20mA Loop	0 to 100	Percent	0.01%
Resistance	10.000	Ohms	0.5mΩ
	100.00	Ohms	5mΩ
	500.0	Ohms	50mΩ
	7000.0	Ohms	500mΩ
Frequency	0.1 to 300,000.0	Hz	0.001Hz
Period	30,000 to 3	µSec	1µS
Temperature	-250.0 to 1800.0	Deg C	0.1%
	-420.0 to 3200.0	Deg F	0.1%
Strain Gauges	-10^4 to 10^4	ppm	1ppm
and Bridges	-10^5 to 10^5	ppm	10ppm
	-10^6 to 10^6	ppm	100ppm
Digital Bit	0 or 1	State	1
Digital Byte (4 bits)	0 to 15	State	1
Digital Average	0.00 to 1.00	State	0.01
Counter	0 to 65535	Counts	1
Phase Encoder	0 to 65535	Counts	1
Analog State	0 or 1	State	1

Temperature

- Thermocouple types B, C, D, E, G, J, K, N, R, S and T, with cold junction compensation and linearization.
- Platinum RTDs, α=0.00385 & 0.003916Ω/Ω/°C, any resistance.
- Nickel RTDs, α=0.005001Ω/Ω/°C, any resistance.
- Copper RTDs, α=0.0039Ω/Ω/°C, any resistance.
- Thermistors, Yellow Springs YSI 400xx series.
- Semiconductors, AD590, LM335, LM34 and LM35.

Time and Date

- Resolution 1 second, accuracy 2 seconds/day.
- Date in DD/MM/YYYY, MM/DD/YYYY, day number and decimal day.
- Time in HH:MM:SS, seconds SSSSS and decimal hour HH.HHHH
- 4 auto-incrementing internal timers (second, minute, hour and day of week) for use in sequencing, alarms, calculations, etc.
- Real time clock used for scan scheduling, date and time stamping of data, alarm timing and in calculations.

Digital Outputs

- 4 TTL/CMOS compatible digital output channels for switched outputs, relay control, alarm annunciation, sensor support.
- Open collector lines, rated to + 30VDC @ 200mA.
- Digital outputs share with the digital input channels.
- 3 LEDs, display backlight and beeper on the display panel.
- Expansion by external modules.

Scanning Input Channels

- 1 immediate scan schedule, can include one or more channels.
- 4 repetitive scan schedules, can include one or more channels.
- Time based scanning in increments of 1 sec, 1 min, 1 hour or 1 day.
- Event based scanning on digital or counter channel events.
- Poll based scanning initiated by host requests.
- Conditional scanning while any digital input is high.

Data Scaling

- Data read from input channels in terms of electrical units can be scaled to engineering units. All data manipulation is then performed on the scaled data.
- Up to 20 definable linear spans, declared as span co-ordinates.
- Up to 20 definable polynomials, from 1st to 5th order.
- Other forms of sensor calibration can be implemented using mathematical expressions.

Data Manipulation

- Statistical data including average, standard deviation, minimum and maximum with date and time of min and max, and integral.
- Delta, rate of delta (differential) and integral between scans.
- Histogram, with definable number of classes.
- Expression evaluation using channel data and constants, arithmetic, logical and relational operators, log, trig, and other functions.

Alarms

- Alarms for monitoring input channels for high and low alarm, inside and outside of range alarm, with definable setpoints.
- Alarms can be combined by AND, OR and XOR operators.
- Optional delay period before an out of range condition is considered a true alarm, or recovery considered a true recovery.
- Alarms can switch digital outputs & display panel LEDs, return text to the host, trigger scanning, and execute Datataker commands.

Data Storage

- Battery backed internal RAM, stores up to 13,650 readings.
- Removable memory cards, store up to 340,000 readings.
- Stack and circular buffer (overwrite) data storage modes.
- No data loss when memory cards are exchanged.
- Stored data can be returned for individual scanning schedules, and for selectable date and time periods.

Data Format

- All data in ASCII floating point, fixed point or exponential formats.
- Data format is user configurable for channel identification, data resolution, units text and delimiters.
- Selectable host computer data format with bi-directional error detection protocol.
- Compatible with spreadsheets, graphic and statistical packages, etc.
- Compatible with most computers, modems, radio, and satellite.

Programming

- All programming is by simple descriptive commands, which are entered from a host computer via the serial interface.
- Commands can be pre-recorded into a memory card, and these are automatically executed whenever a memory card is inserted.

Display and Keypad (DT605 only)

- LCD type, 2 line x 16 character, backlit, alphanumeric.
- Displays channel data, alarm status and system information.
- 5 key keypad for display selection, scrolling, backlight.
- Keypad also provide 4 user definable function keys.
- 3 LEDs, beeper and flashing backlight provide warnings for alarms.

Host Communications

- RS232, full duplex. Also supports RS423.
- 300, 1200, 2400 and 9600 baud, switch selectable.
- Bi-directional XON/XOFF protocol.
- Compatible with computers, terminals, modems, satellite ground terminals, serial printers, etc.

Network Communications

- RS485, with error correcting protocol.
- Connected via a twisted pair, maximum 1000 metres.
- Up to 32 loggers can be in a Datataker network, with one host.

Power Supply

- Voltage 9 – 18VAC or 11 – 24VDC external power.
- Mains powered from 12VAC/DC mains adaptor.
- Automatically selects low power standby (sleep) mode.
- Current draw 120mA normal power mode, 400mA when charging internal battery, <350µA low power (sleep) mode.
- Internal 1.2Ah gel cell battery, recharged by external power.
- Approximate battery life for different schedules and battery sizes

Sampling 10 channels every	1.2Ah Gel Cell Battery	17 Ah Alkaline Battery
Continuously	5 hours	3 days
1 minute	12 days	160 days
15 minutes	60 days	800 days
1 hour	110 days	1100 days

Mechanical Specification

- Robust modular construction using powder coated steel.
- Can be used directly, or housed in fixed or portable enclosures.
- Length 270mm (10.5 inches), Width 110mm (4.3 inches).
- Height 85mm (3.3 inches) with no memory card inserted.
- Height 105mm (4.2 inches) with a memory card inserted.
- Weight 2.4Kg.
- Signal I/O connection by screw terminals.
- Operating temperature –20 to 70 °C, humidity 95%.

Accessories Included

- 110/240VAC mains/line power adaptor.
- 1.2Ah gel cell internal battery.
- RS232 communications cable for IBM™ and compatibles.
- Getting Started Manual and User's Manual.
- DeTerminal software package for IBM™ and compatibles.

Options

- Channel expansion modules with 10 differential/30 single ended analog inputs, and 20 digital inputs, and 10 digital outputs.
- Portable carry case, clamshell design, waterproof (IP67, NEMA 6).
- Industrial quality steel enclosures (IP65, NEMA 5).
- 4Ah rechargable gel cell or 17Ah alkaline battery.
- 64K Datataker memory card, stores 16,000 readings.
- 256K Datataker memory card, stores 81,000 readings.
- 512K PCMCIA memory card, stores 170,000 readings.
- 1M PCMCIA memory card, stores 340,000 readings.
- PCMCIA memory card adaptor.
- Memory card readers.
- Communications cable for Apple Macintosh™.
- DeCipher Plus software package for IBM™ and compatibles.

Ordering

• Datataker with display	DT605
• Datataker without display	DT505
• Channel expansion module	CEM
• Portable carry case	PE
• Small industrial enclosure	SIE
• Large industrial enclosure	LIE
• Small industrial cabinet	SIC
• 64K Datataker memory card	MC-64
• 256K Datataker memory card	MC-256
• 512K PCMCIA memory card	MC-512P
• 1M PCMCIA memory card	MC1024P
• PCMCIA memory card adaptor	MC-ADP
• Memory Card Reader - RS232 Interface	MC-RS
• Memory Card Reader - Centronics Interface	MC-RP

DATA ELECTRONICS (AUST) PTY LTD 7 SEISMIC CRT ROWVILLE 3178 AUSTRALIA. PH: 03 764 8600 FAX: 03 764 8997

The proprietary software that has been written for the *505 Datataker* is called *De Terminal*. This is used to preset the channels and form of the incoming data.

APPENDIX J

Photographic stills of exemplary stages in the combustion behaviour of upholstered furniture

Progression of fire in single seater armchair (Polyurethane foam + polypropylene fabric)

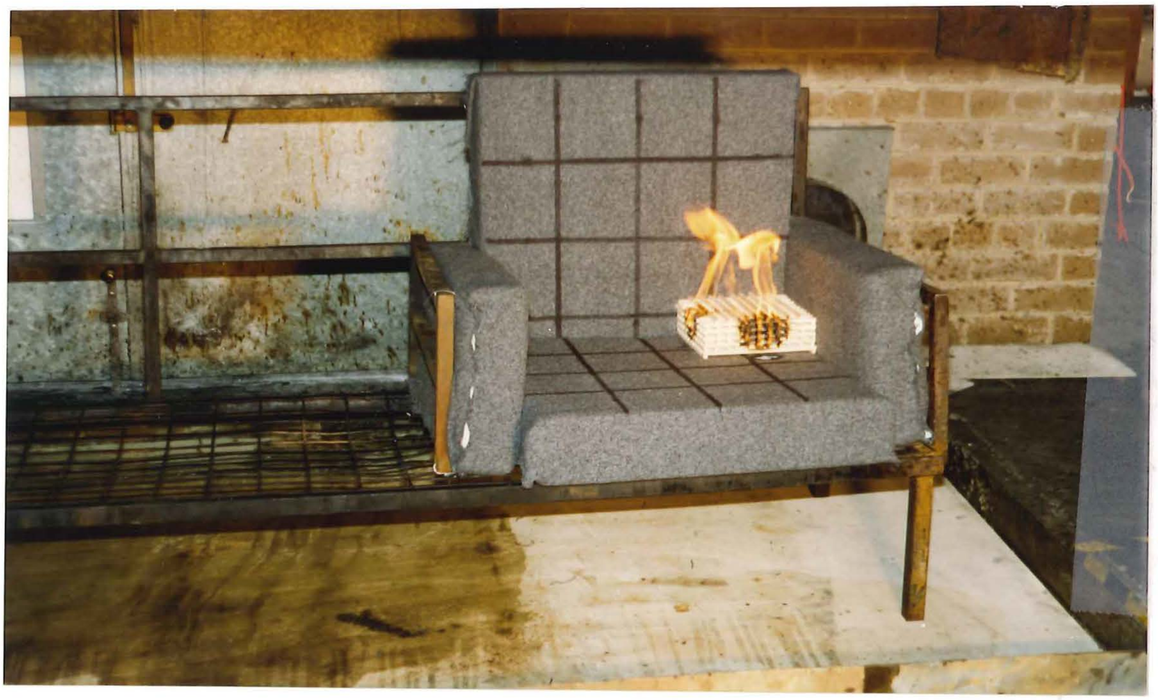


Figure I 1 shows the start of a test (*Standard Polyurethane* foam + polypropylene fabric) with the ignition crib having been just set alight.

Figure I 2 shows the same test a short time later (approx 60 seconds). Of special interest is that the foam has already melted through underneath the ignition crib and is starting to form a pool under the chair. Notice how the polypropylene fabric tears and shrinks away from the fire, exposing the foam underneath to direct attack.

Figure I 3 shows the same test at about 90 seconds. The seat of the chair is now fully involved. The runoff melted foam has now formed a substantial pool fire below.

Figure I 4 shows the same chair configuration but this time with the cotton/linen fabric. Notice how the cotton/linen fabric contains the melted foam, preventing it from dripping underneath the chair and potentially forming a pool fire below. Note that the fabric stays in place and protects the foam.

Figure I 5 illustrates potential ferocity of a single seater armchair, which is close to, but hasn't yet reached its' peak HRR. This specimen was the *Standard Polyurethane* foam + polypropylene fabric combination. Notice how the foam has not yet melted significantly through to the floor as was typical of this type of construction.

Progression of fire for a cotton/linen fabric three seater sofa (centre ignited)

Figure I 6 shows a centre ignited three seater, cotton/linen fabric specimen burn test Notice how the flame front on the fabric is very defined and straight

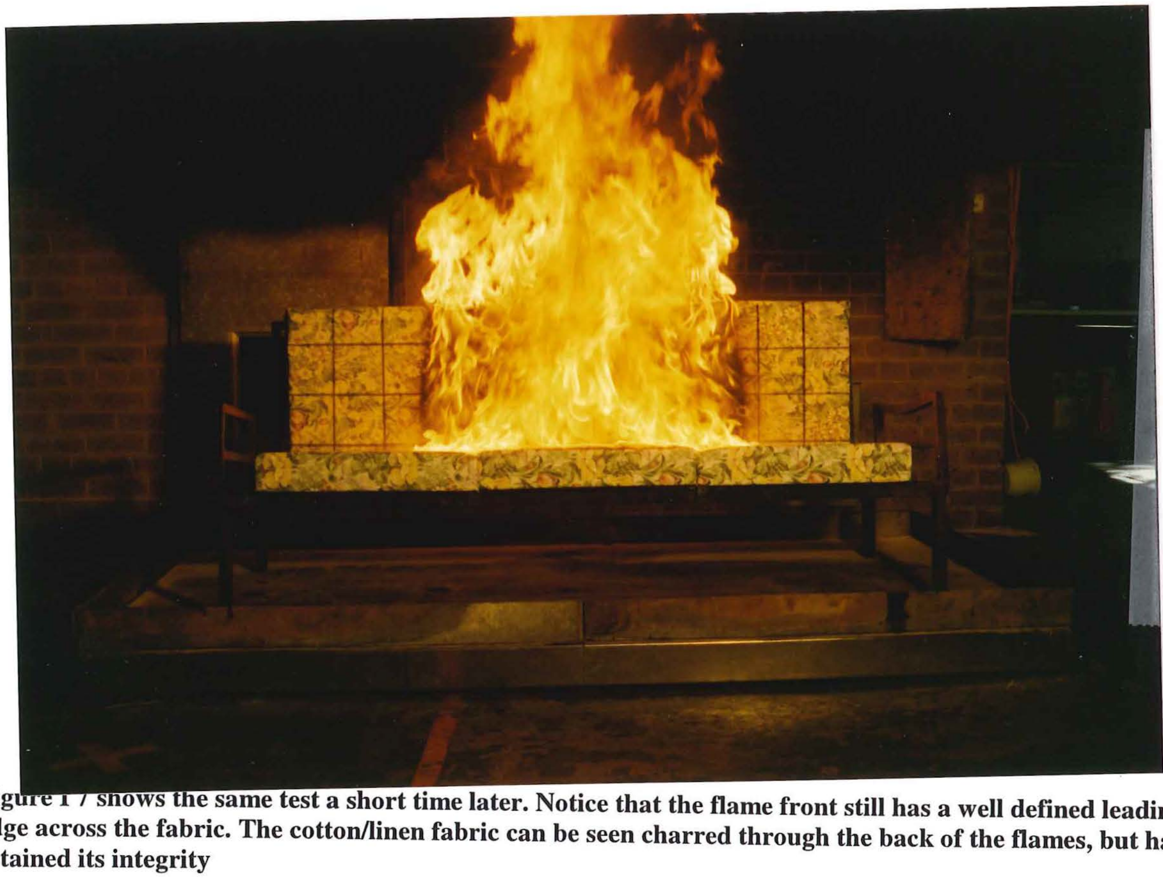


Figure I 7 shows the same test a short time later. Notice that the flame front still has a well defined leading edge across the fabric. The cotton/linen fabric can be seen charred through the back of the flames, but has retained its integrity

Progression of fire for a polypropylene fabric three seater sofa (centre ignited)

Figure I 8 shows the three seater, as viewed offset from centre, almost fully involved in flame. Notice the pool fire burning below the sofa, due to the run-off-melted foam that has dripped to the floor.

Figure I 9 shows the same test a short time later, viewed from a front angle. A substantial pool fire below the sofa is now burning. Notice how the fabric has peeled away from the fire, exposing the foam.

Progression of fire for a polypropylene fabric three seater (right hand ignition)

Figure I 10 shows the fire in the beginning stages of development. Burning is confined just to the first seat and back cushion. The peeling back of the polypropylene fabric can be clearly seen around the edges of the fire.

Figure I 11 shows the fire a short time later. The fire has now progressed to involving half the sofa, and small pool fires are starting to form below. Notice that the flame front is confined just to the exposed foam.

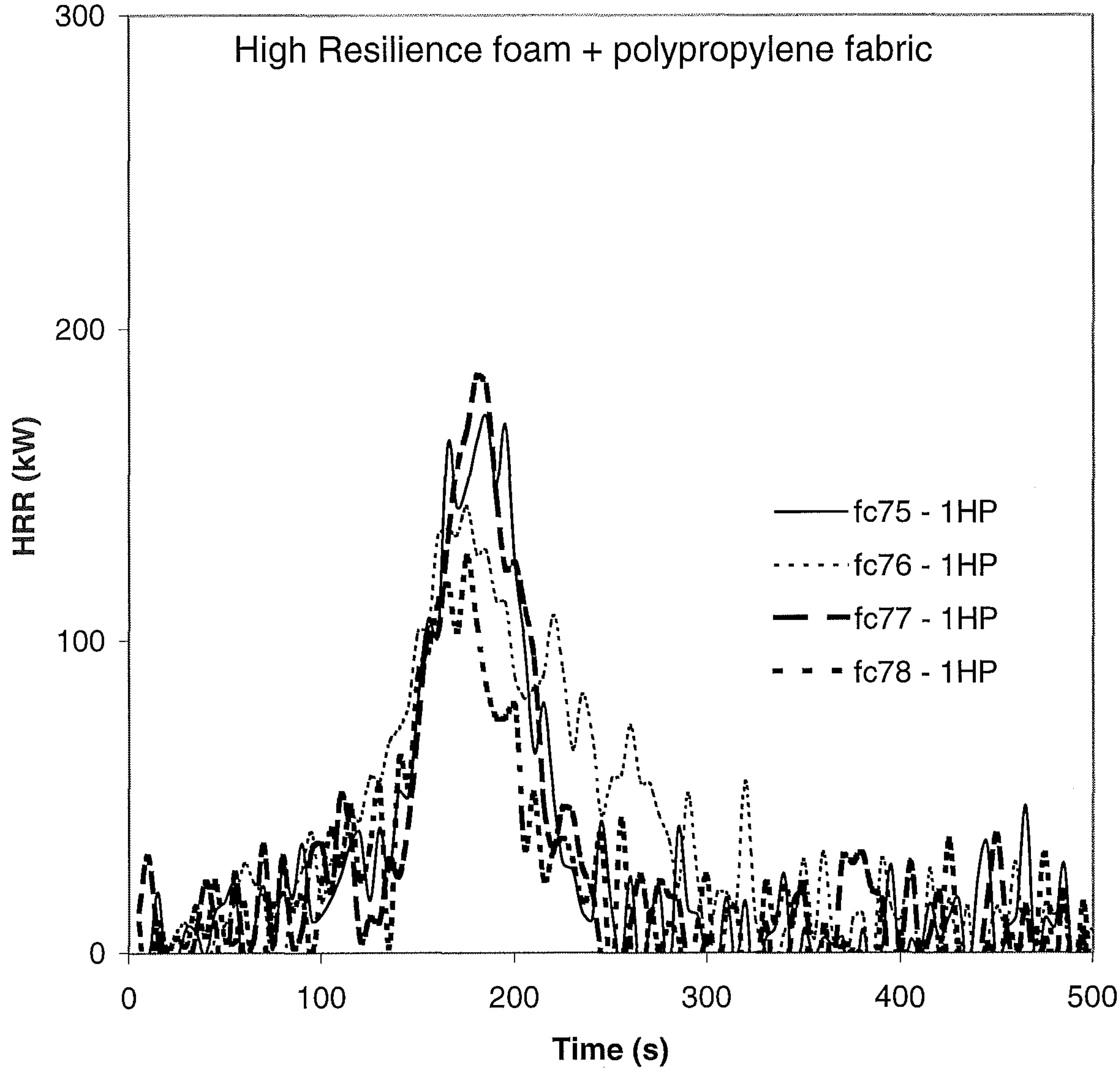
Figure I 12 shows the same fire about 45 seconds later. Notice the now extensive pool fire burning below the sofa. The far left-hand cushions are just now starting to get involved in flames.

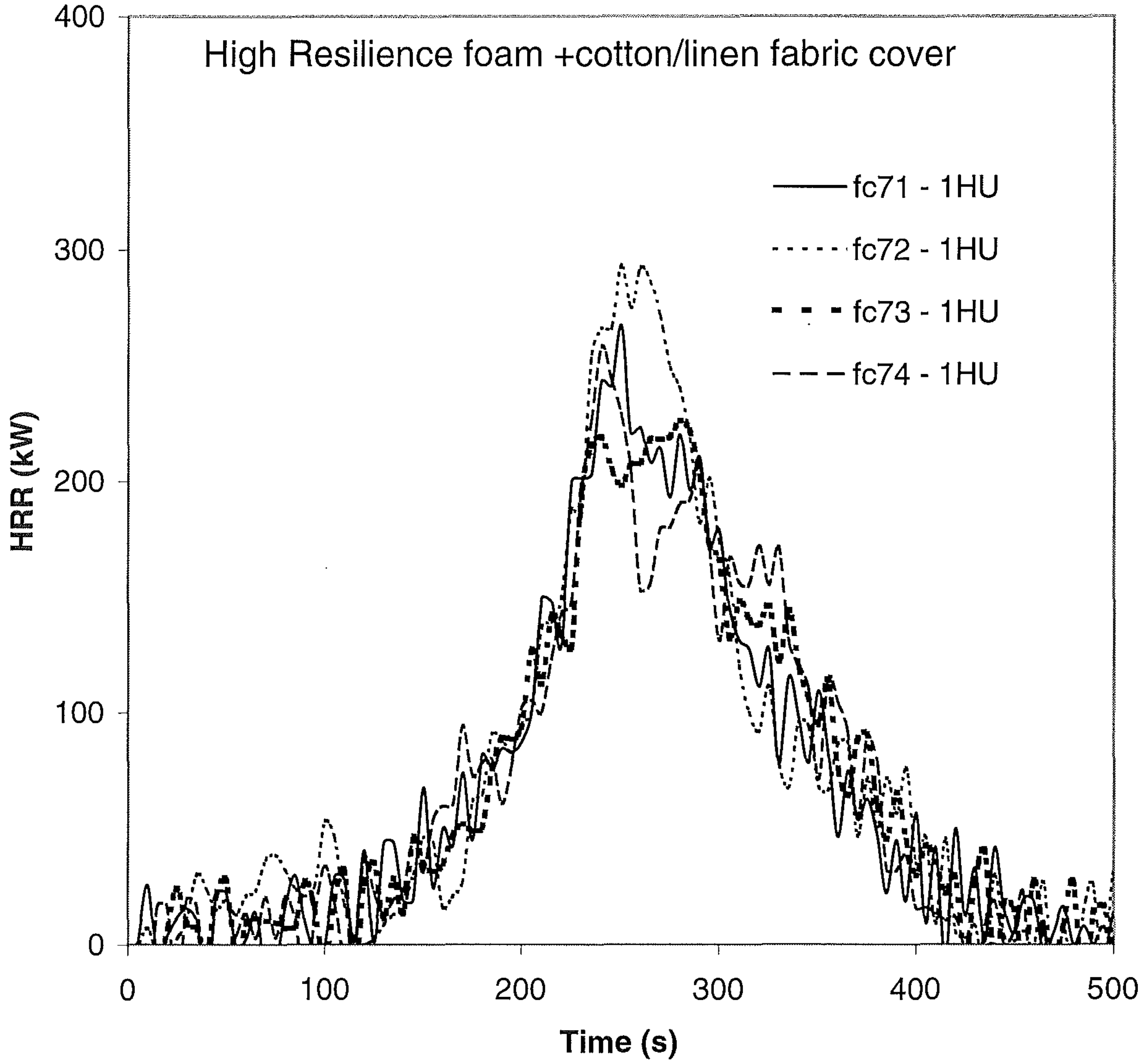
Figure I 13 shows the same fire a short time later, as viewed from a right of centre angle. The fire is now almost completely a pool fire. Notice the wood crib embers have all fallen through the foam bottom.

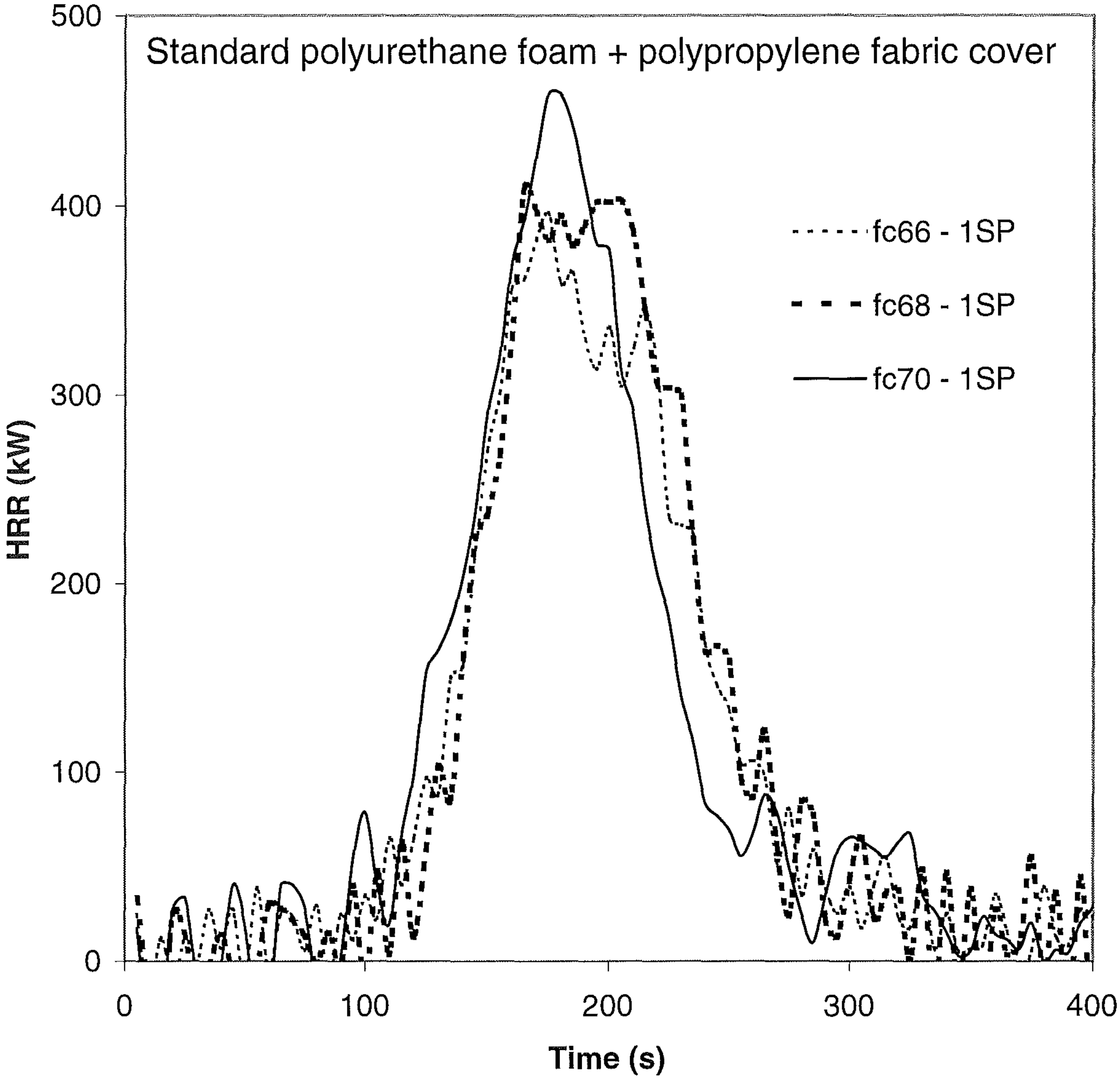
APPENDIX K

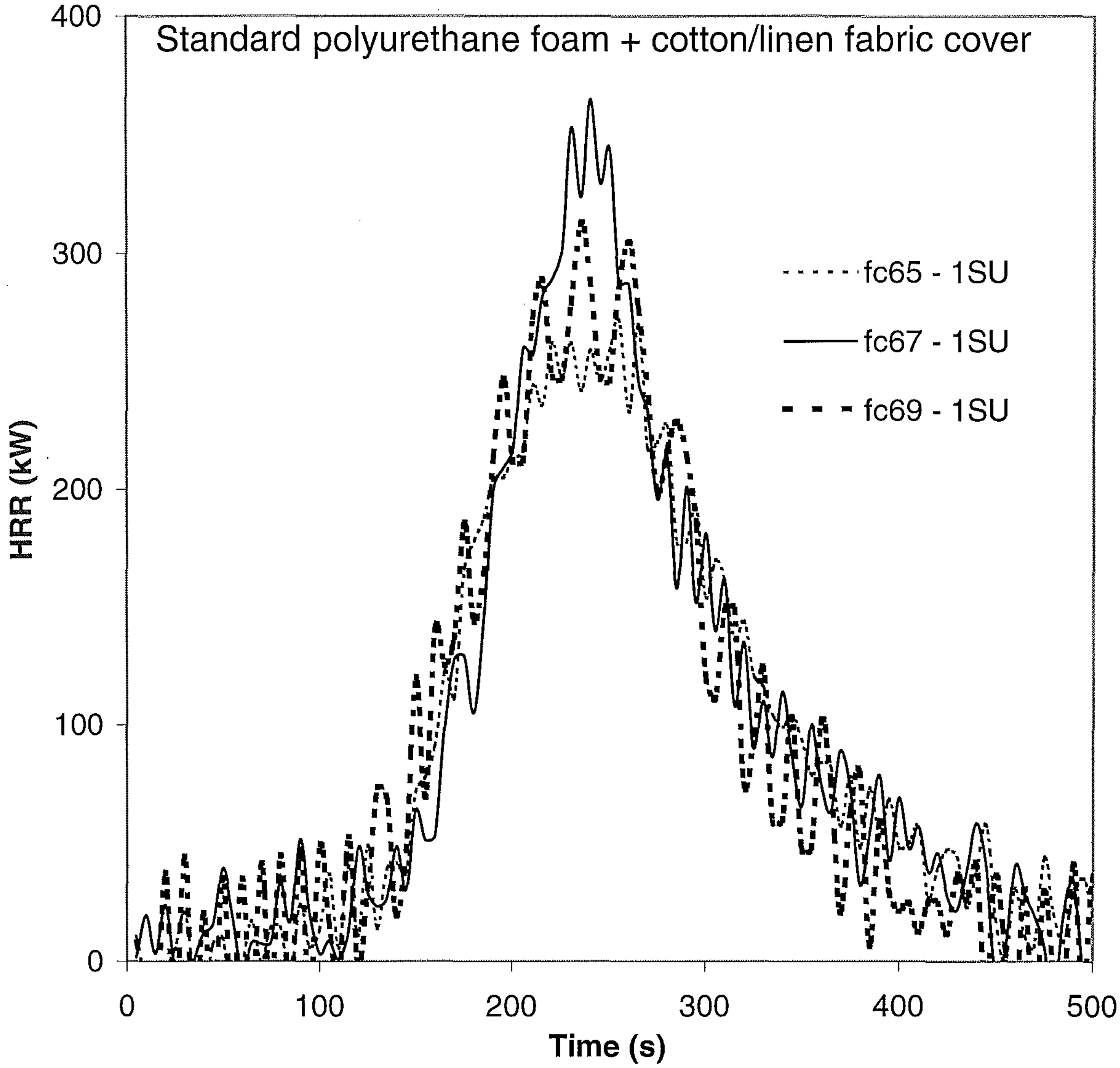
Full-size HRR curves for the CSIRO furniture tests

One seater series

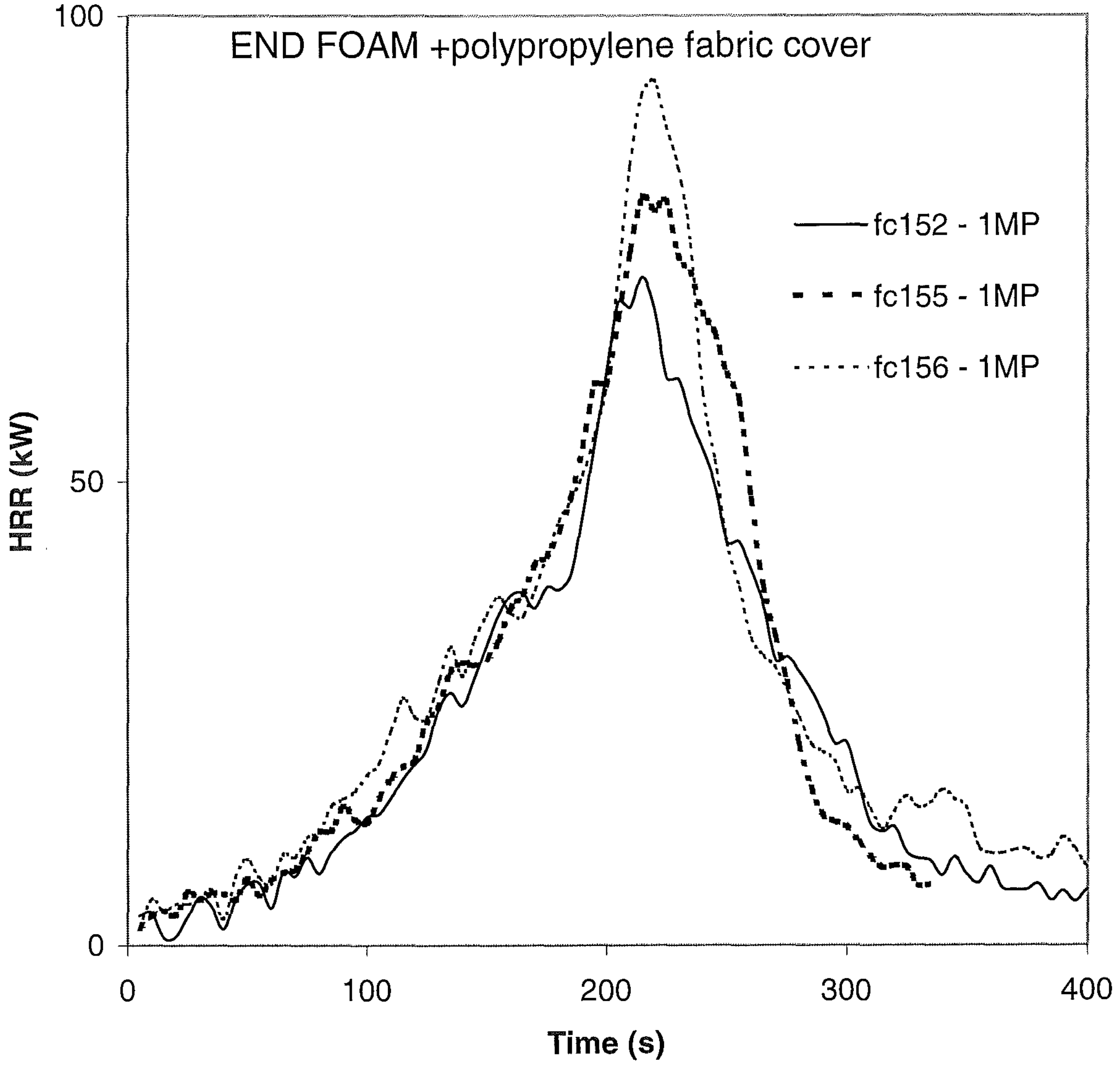



High Resilience foam +cotton/linen fabric cover
fc71 - 1HU
fc72 - 1HU
fc73 - 1HU
fc74 - 1HU
HRR (kW)
Time (s)
0
100
200
300
400
500

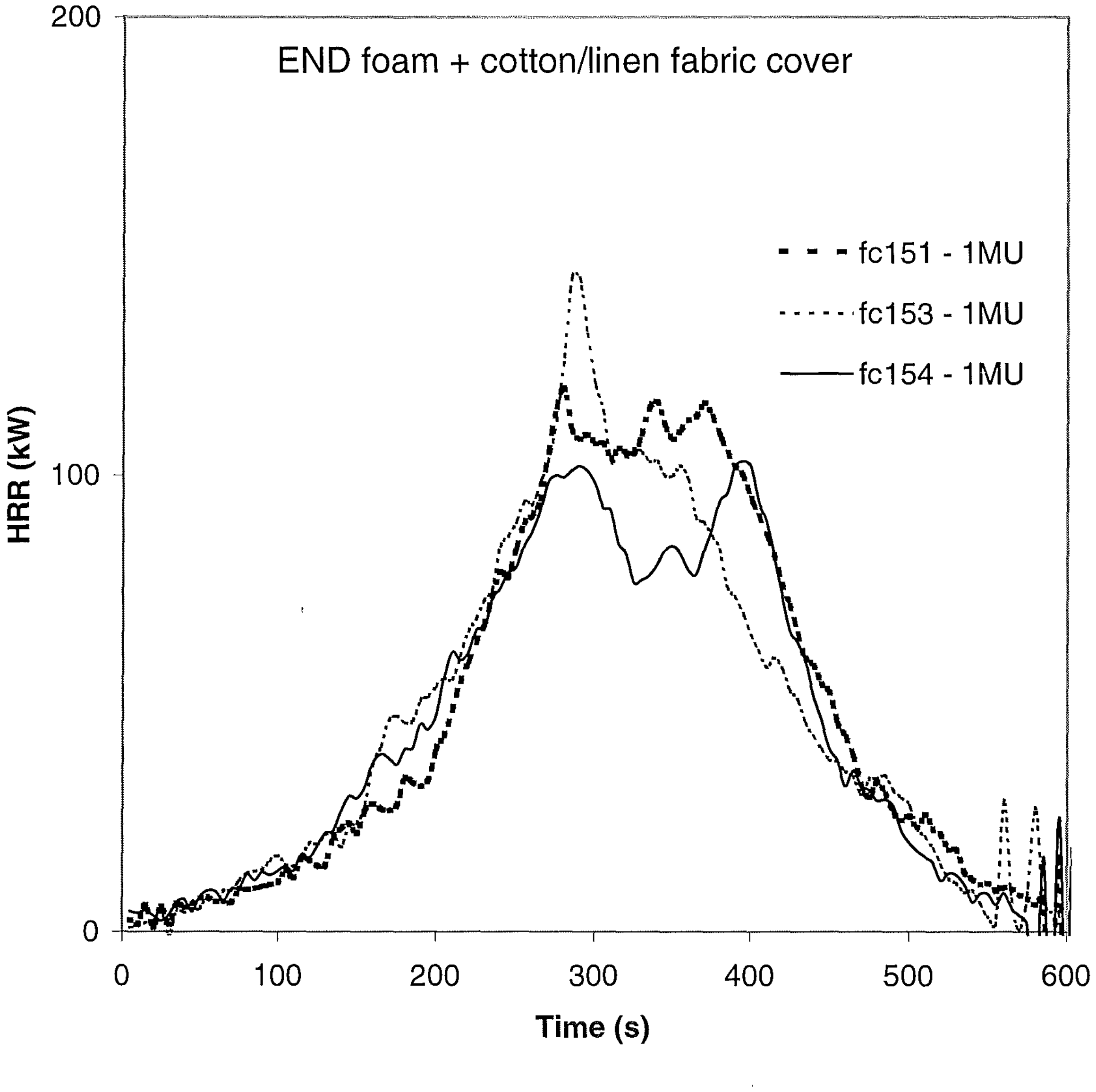

Standard polyurethane foam + polypropylene fabric cover
fc66 - 1SP
fc68 - 1SP
fc70 - 1SP
HRR (kW)
Time (s)
0
100
200
300
400
500



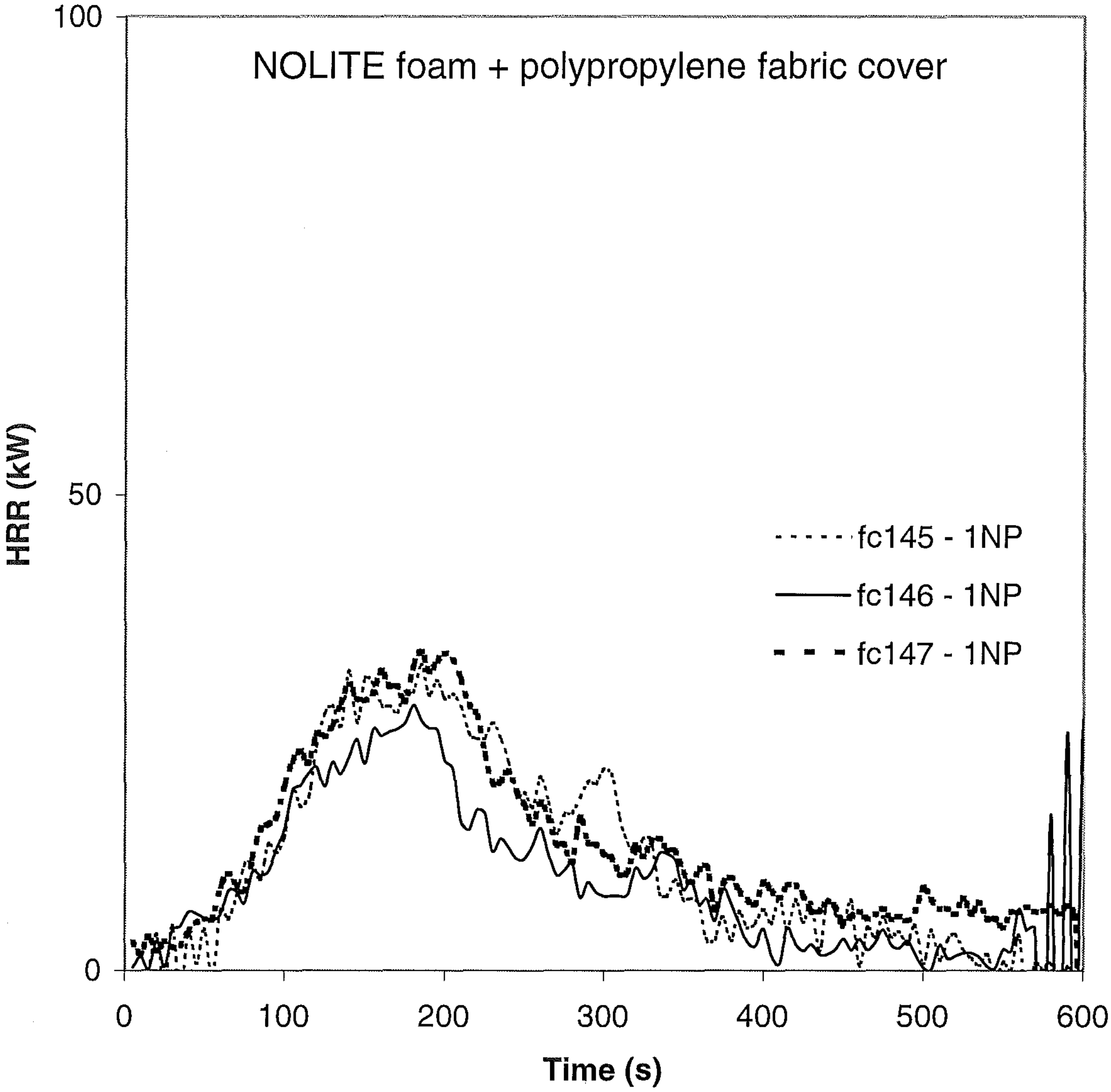
Standard polyurethane foam + cotton/linen fabric cover
fc65 - 1SU
fc67 - 1SU
fc69 - 1SU
HRR (kW)
Time (s)
0
100
200
300
400
500



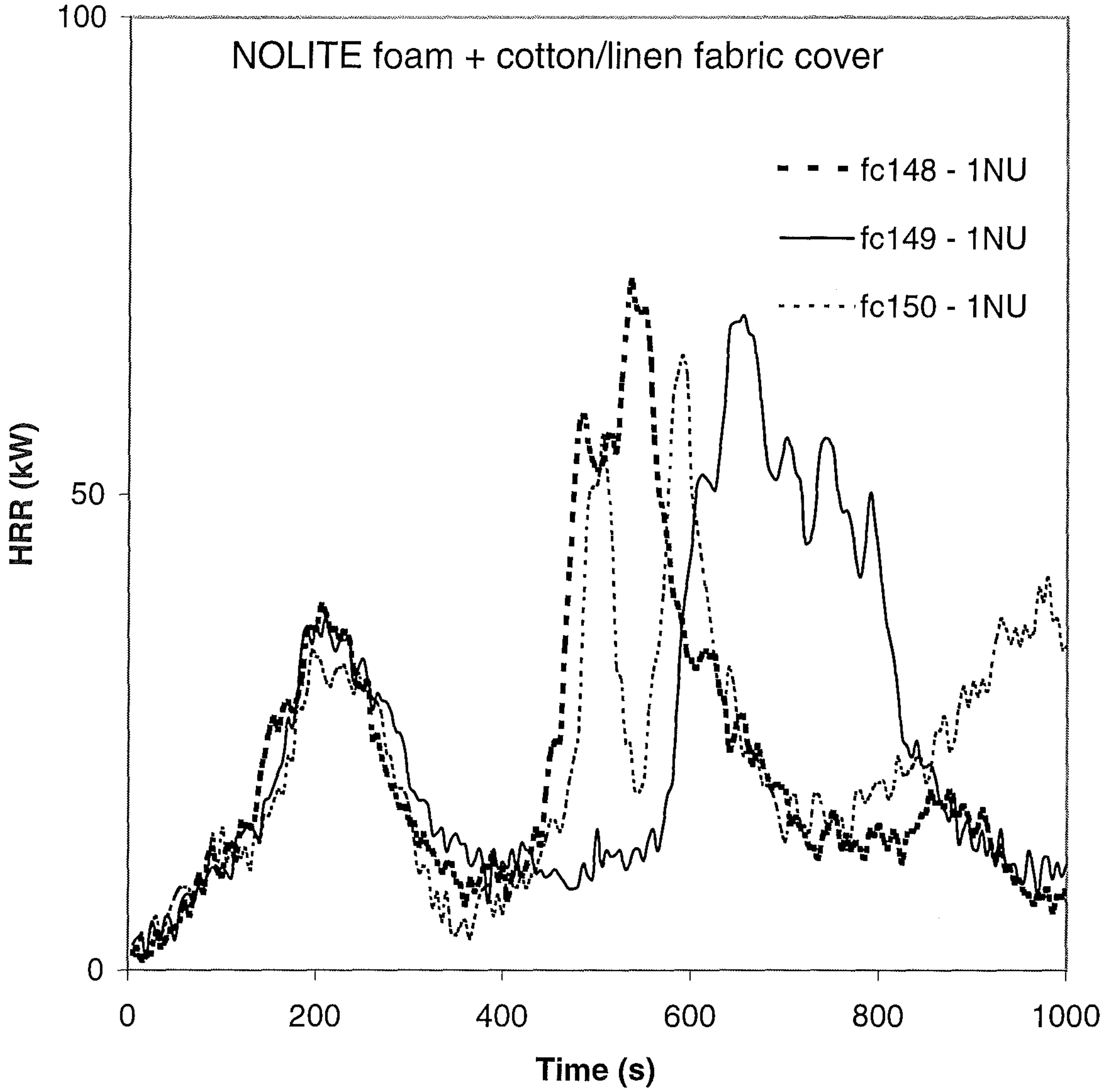
END FOAM +polypropylene fabric cover
fc152 - 1MP
fc155 - 1MP
fc156 - 1MP
HRR (kW)
Time (s)
100
50
0
0
100
200
300
400



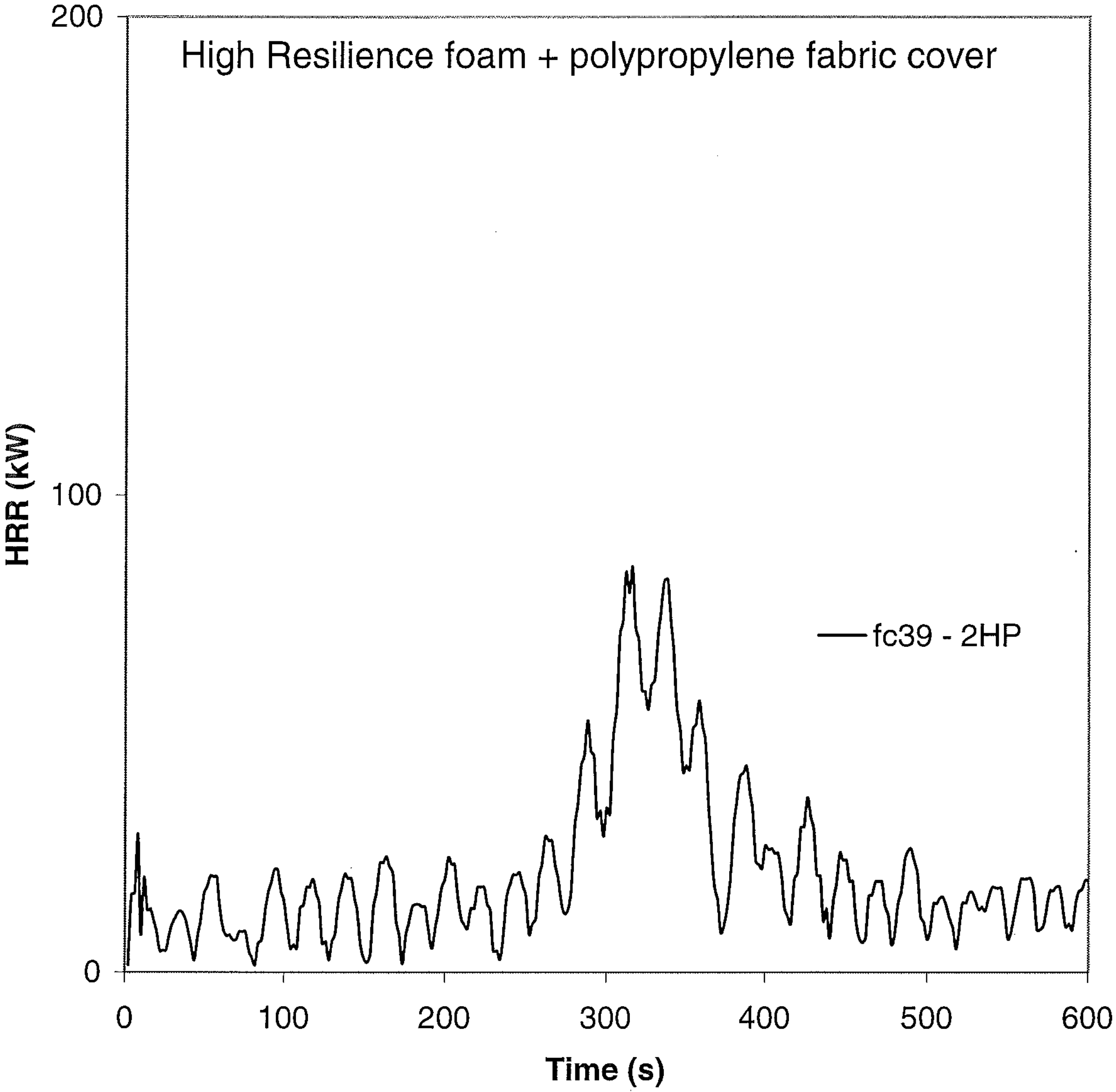
END foam + cotton/linen fabric cover
fc151 - 1MU
fc153 - 1MU
fc154 - 1MU
HRR (kW)
Time (s)
0
100
200
300
400
500
600

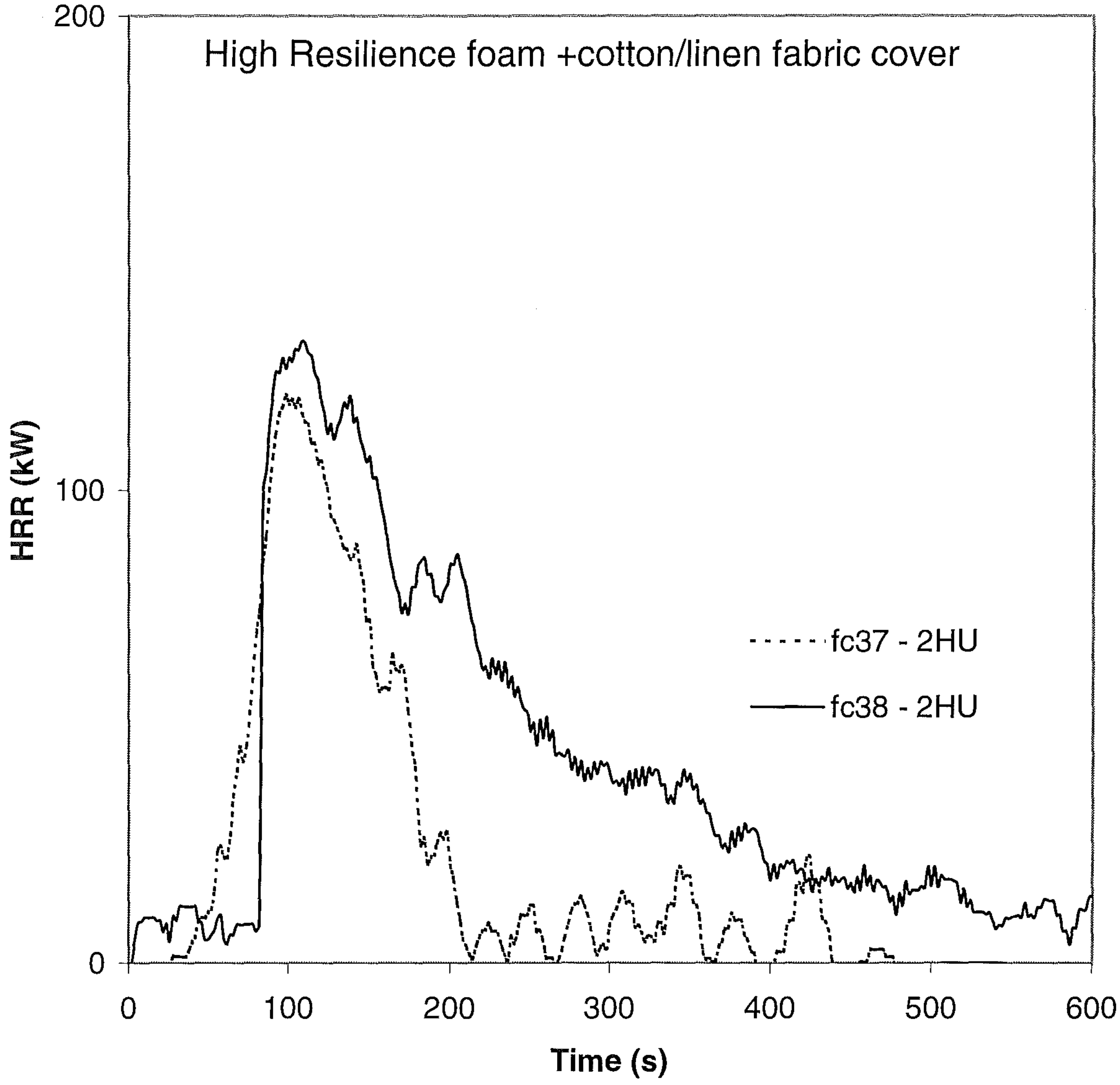


NOLITE foam + polypropylene fabric cover
HRR (kW)
100
50
0
fc145 - 1NP
fc146 - 1NP
fc147 - 1NP
0
100
200
300
400
500
600
Time (s)

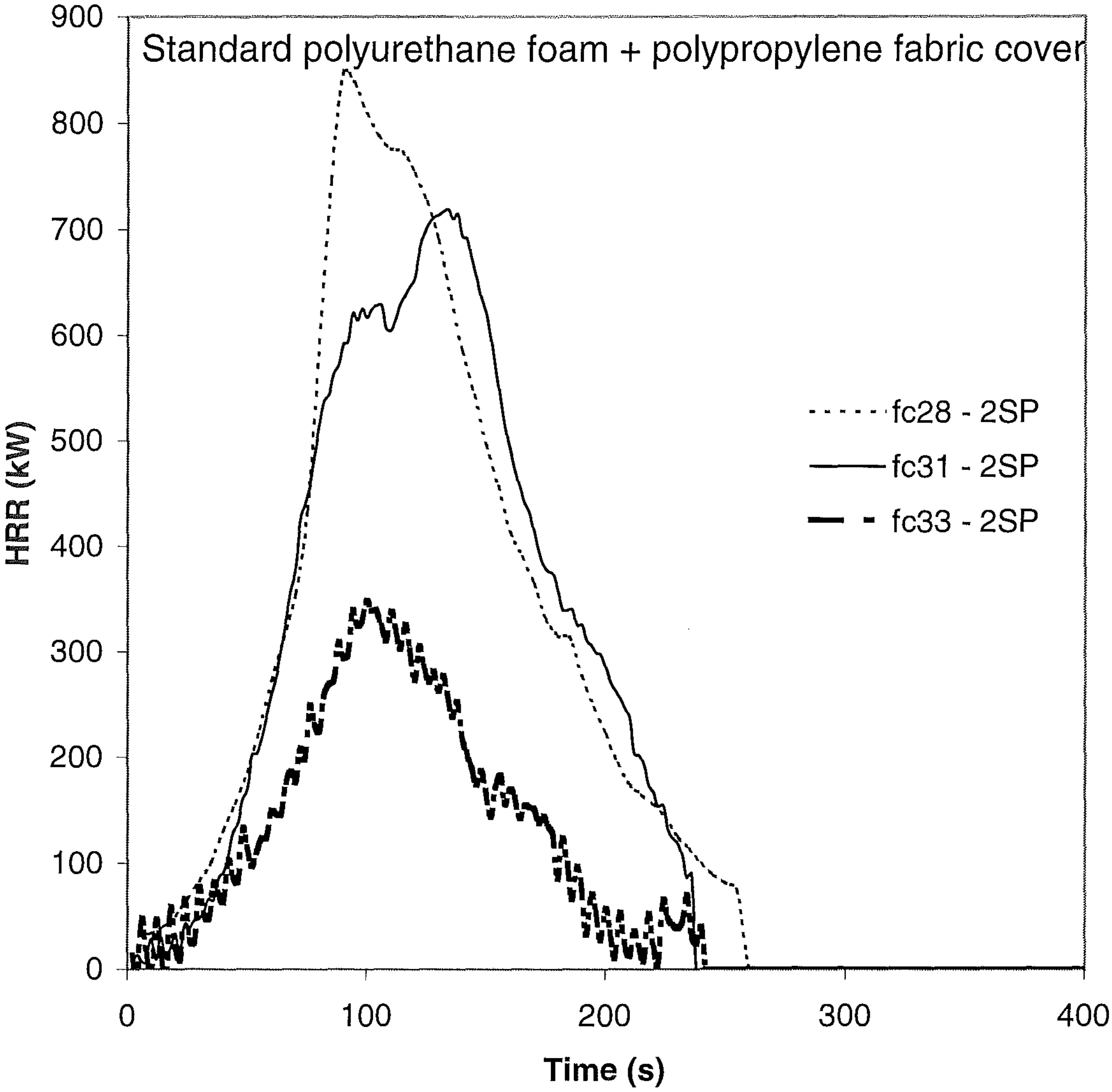

NOLITE foam + cotton/linen fabric cover
fc148 - 1NU
fc149 - 1NU
fc150 - 1NU
HRR (kW)
Time (s)
100
50
0
0
200
400
600
800
1000

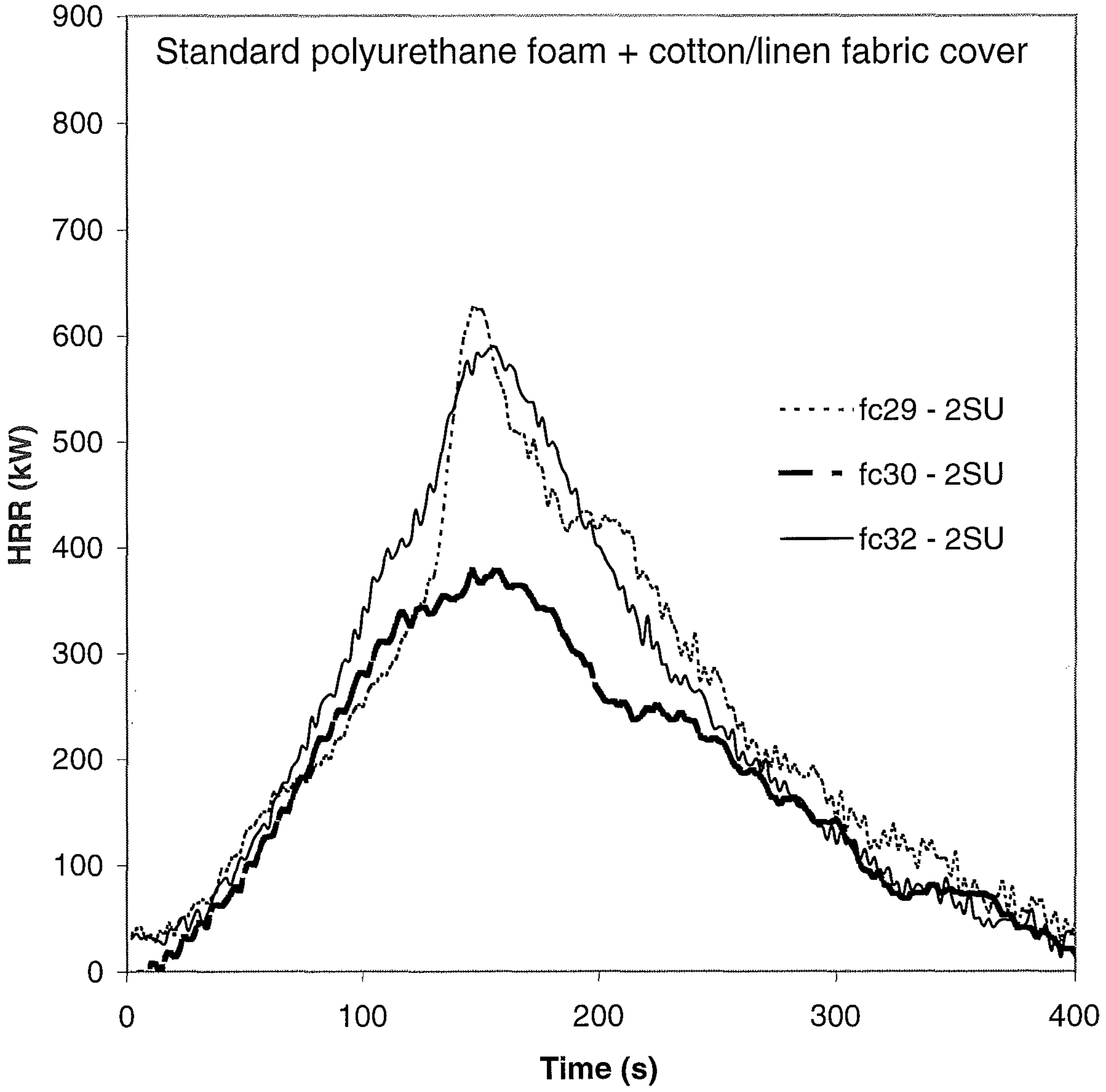
Two seater series



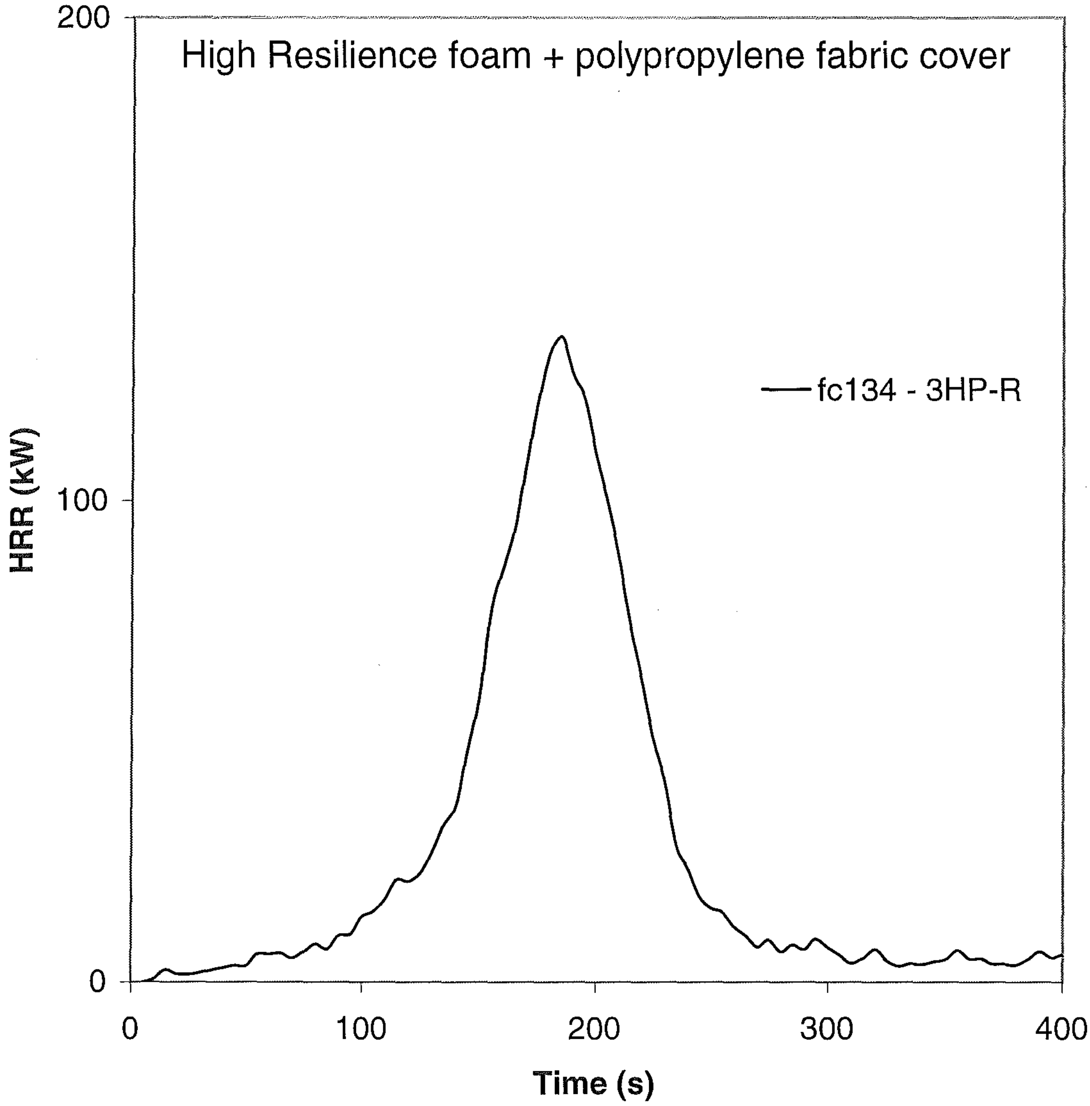


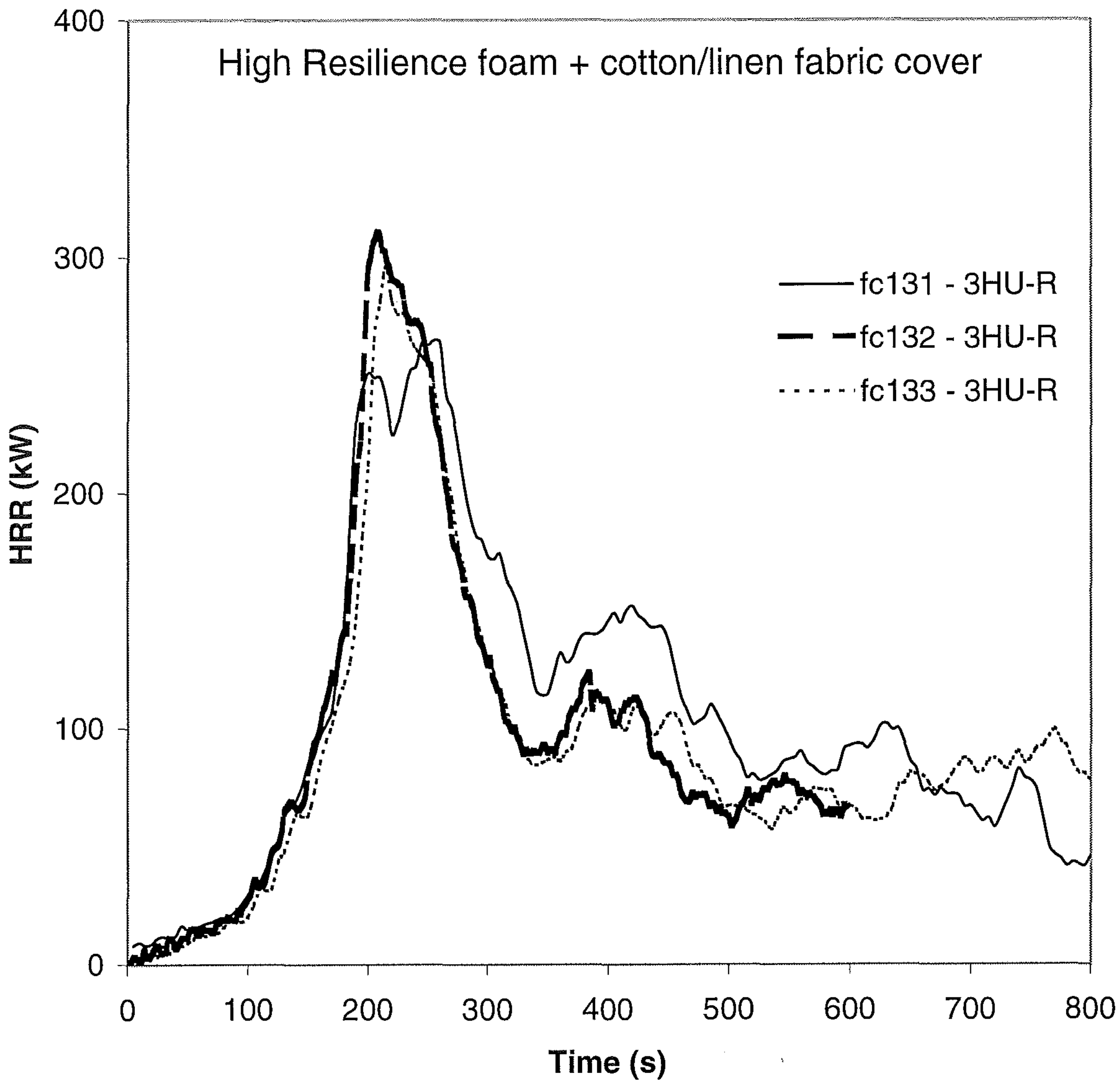
High Resilience foam +cotton/linen fabric cover
HRR (kW)
200
100
0
0
100
200
300
400
500
600
Time (s)
fc37 - 2HU
fc38 - 2HU

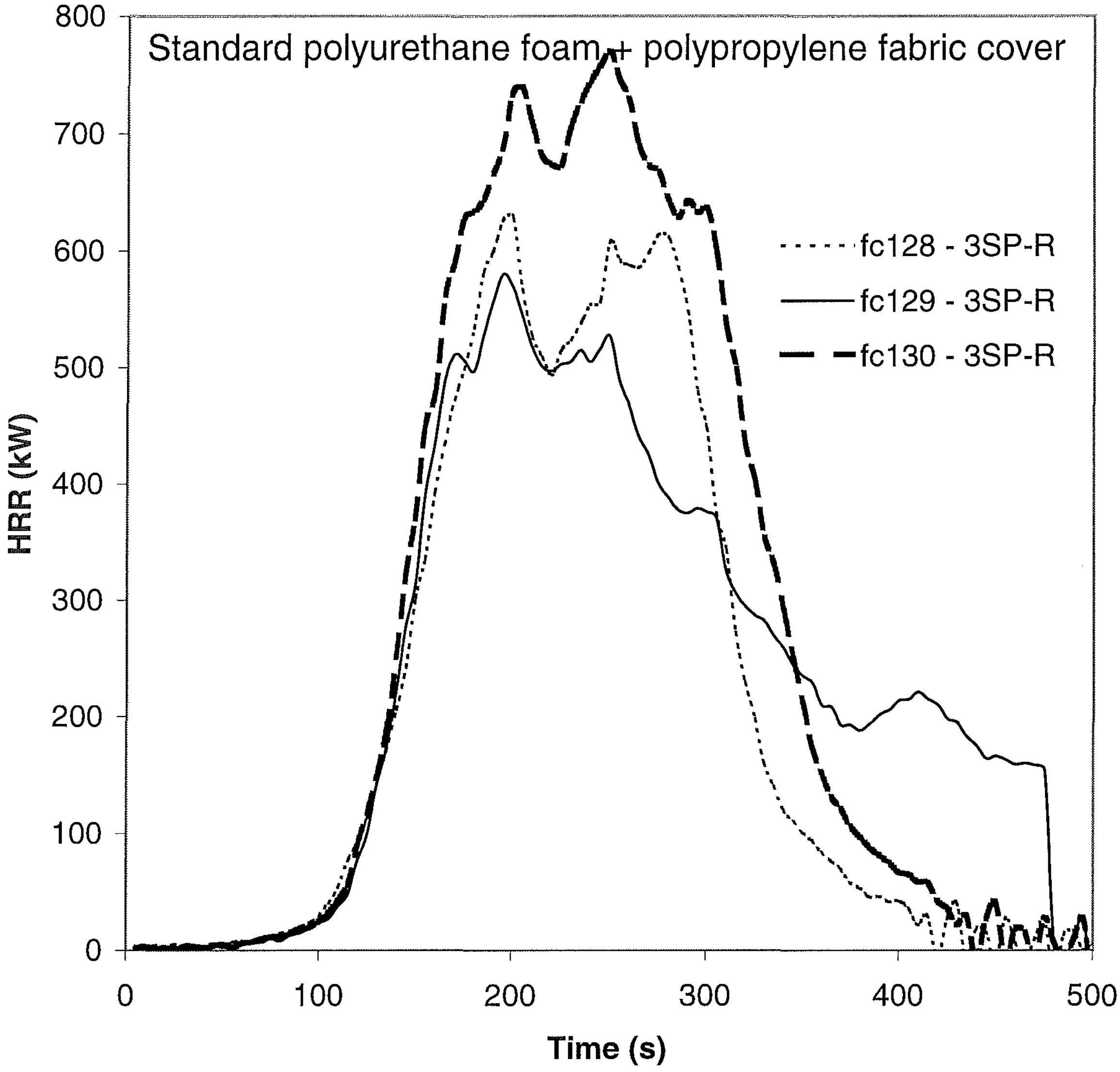

Standard polyurethane foam + polypropylene fabric cover
HRR (kW)
Time (s)
fc28 - 2SP
fc31 - 2SP
fc33 - 2SP
0
100
200
300
400
500
600
700
800
900
0
100
200
300
400


Standard polyurethane foam + cotton/linen fabric cover
HRR (kW)
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
Time (s)
fc29 - 2SU
fc30 - 2SU
fc32 - 2SU

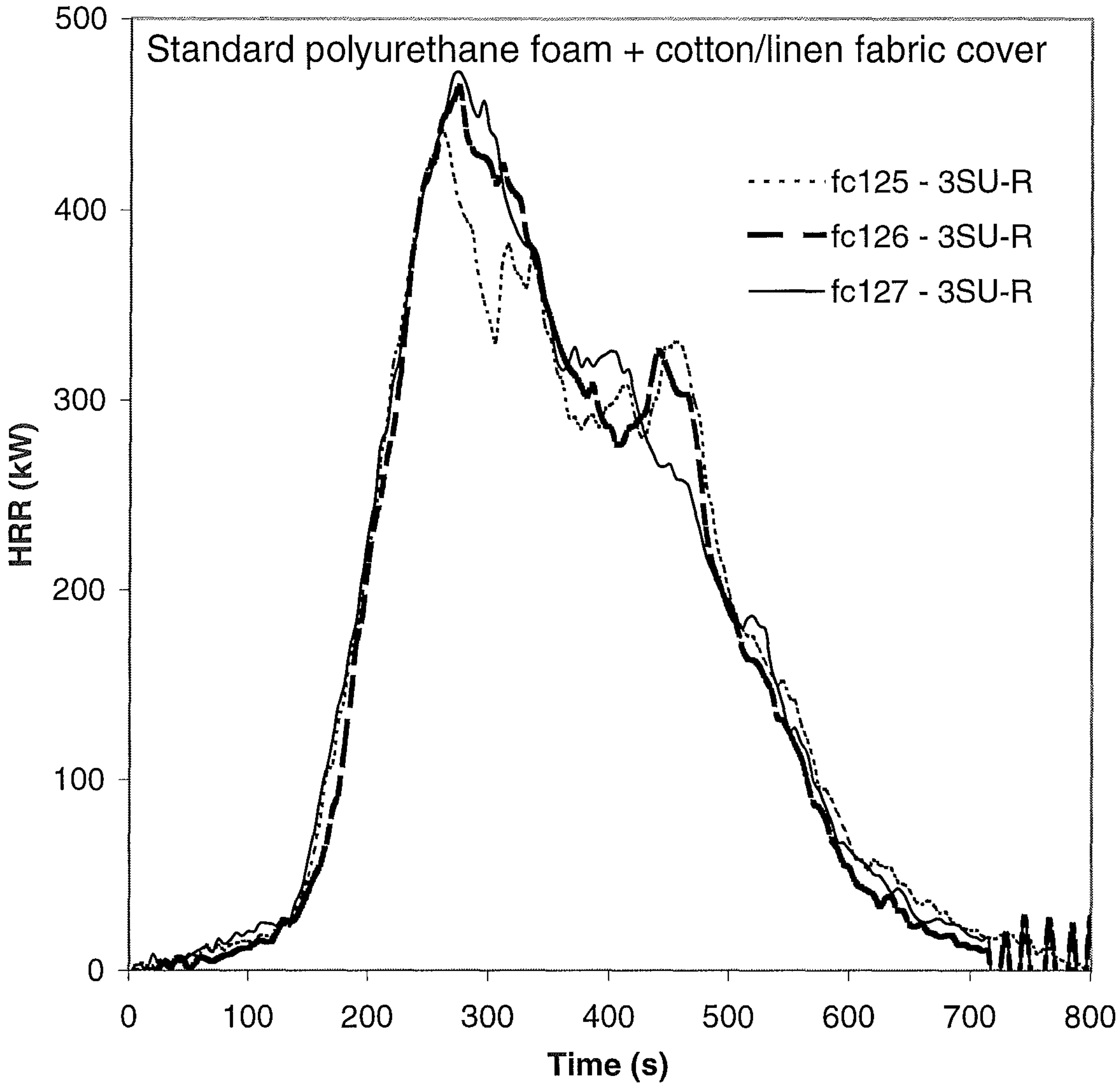
Three seater series



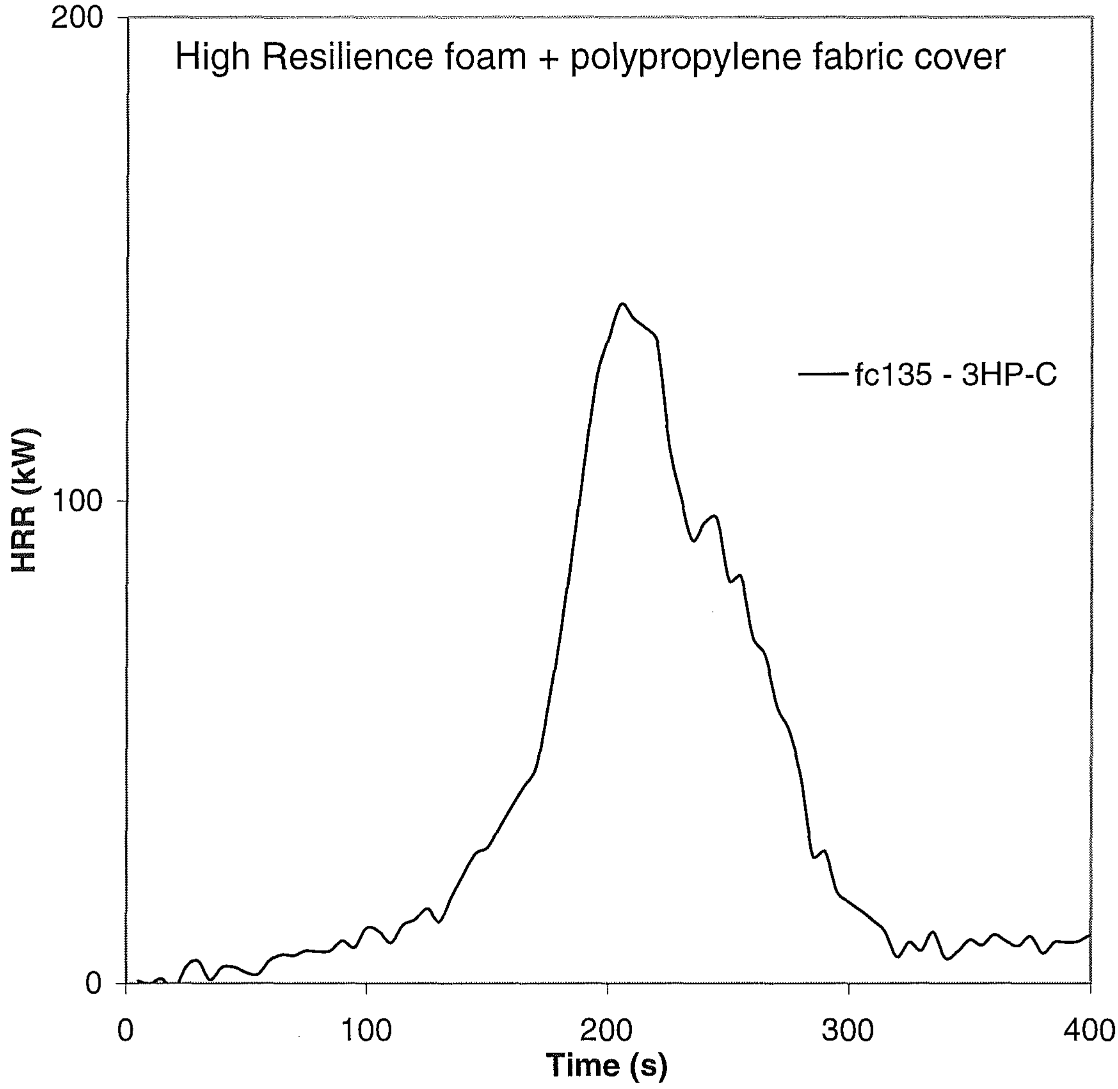

High Resilience foam + cotton/linen fabric cover
fc131 - 3HU-R
fc132 - 3HU-R
fc133 - 3HU-R
HRR (kW)
Time (s)
0
100
200
300
400
500
600
700
800



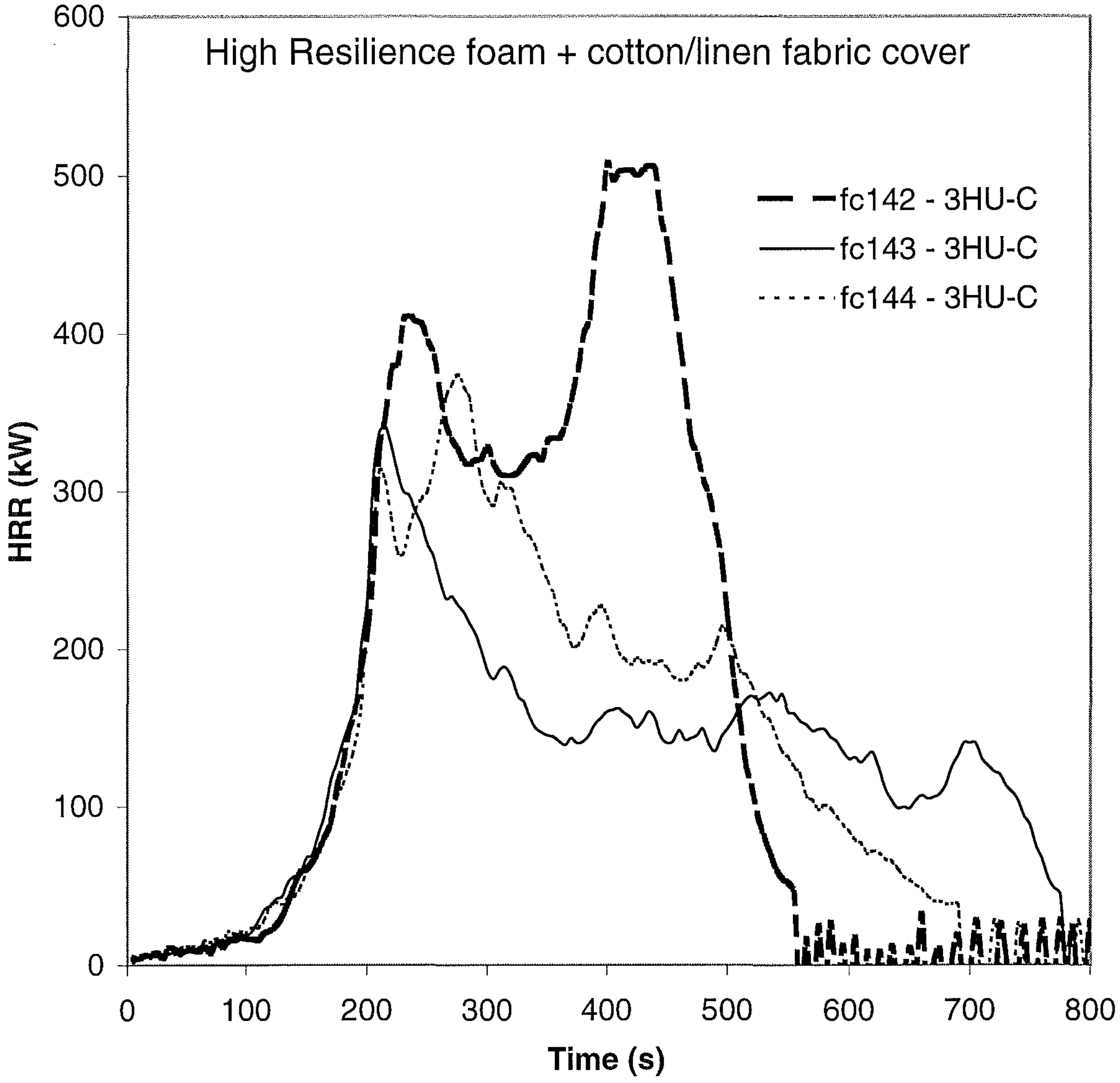
Standard polyurethane foam + polypropylene fabric cover
fc128 - 3SP-R
fc129 - 3SP-R
fc130 - 3SP-R
HRR (kW)
Time (s)
0
100
200
300
400
500
600
700
800



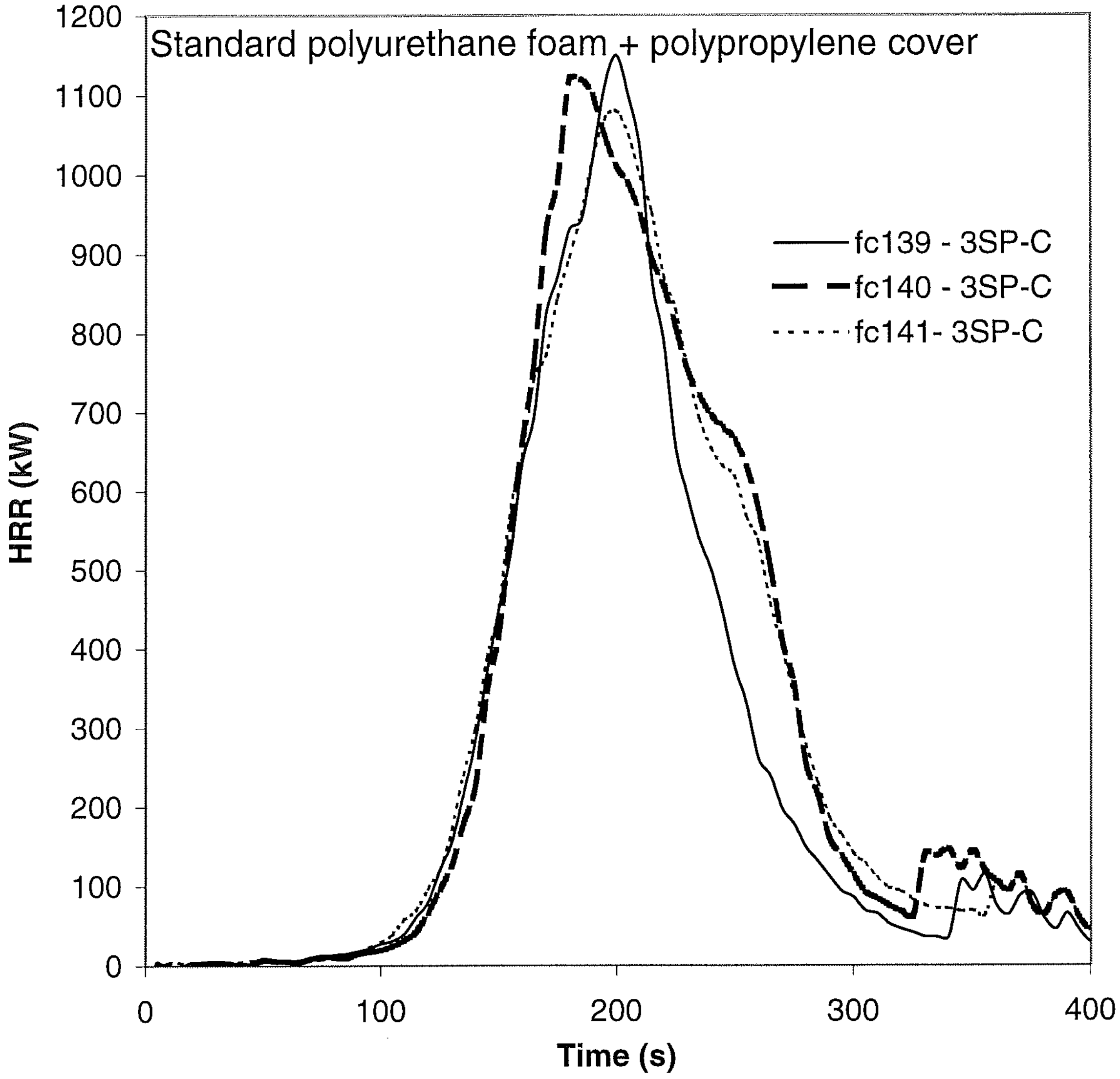
Standard polyurethane foam + cotton/linen fabric cover
fc125 - 3SU-R
fc126 - 3SU-R
fc127 - 3SU-R
HRR (kW)
Time (s)
0
100
200
300
400
500
600
700
800

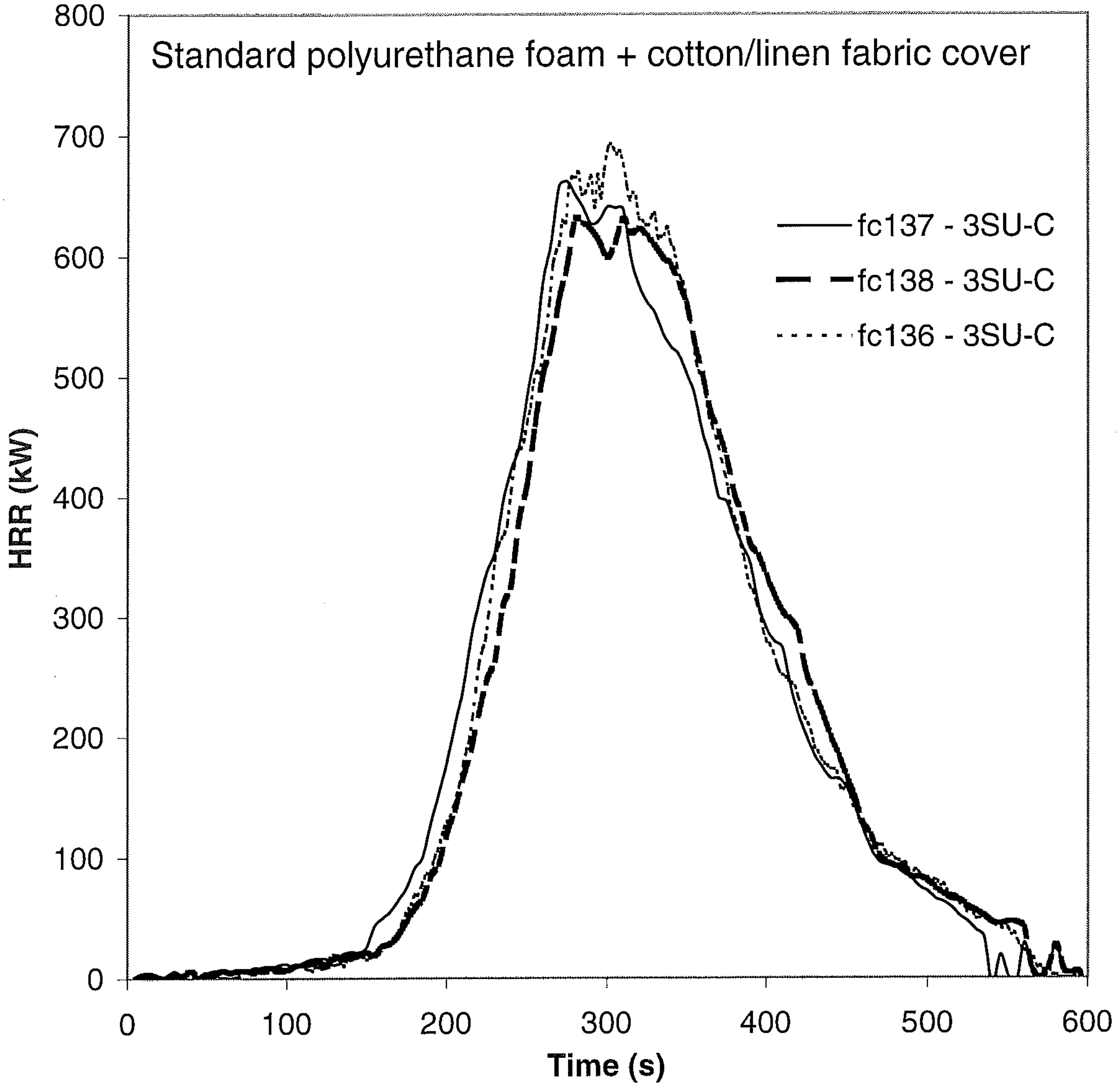


High Resilience foam + polypropylene fabric cover
fc135 - 3HP-C
HRR (kW)
200
100
0
0
100
200
300
400
Time (s)



High Resilience foam + cotton/linen fabric cover
HRR (kW)
Time (s)
fc142 - 3HU-C
fc143 - 3HU-C
fc144 - 3HU-C
0
100
200
300
400
500
600
700
800


Standard polyurethane foam + polypropylene cover
fc139 - 3SP-C
fc140 - 3SP-C
fc141- 3SP-C
HRR (kW)
Time (s)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0
100
200
300
400



Standard polyurethane foam + cotton/linen fabric cover
fc137 - 3SU-C
fc138 - 3SU-C
fc136 - 3SU-C
HRR (kW)
Time (s)
0
100
200
300
400
500
600
700
800